"A TEST OF THE PENMAN COMBINATION MODEL

FOR POTENTIAL EVAPOTRANSPIRATION"

A TEST OF THE PENMAN COMBINATION MODEL FOR POTENTIAL EVAPOTRANSPIRATION

by

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SCOPE AND CONTENTS:

The Penman combination model for potential evapotranspiration, using the improved wind function of Businger (1956), and measured net radiation, was tested for daily and hourly totals, over an irrigated perennial ryegrass surface at Simcoe, Norfolk County, Southern Ontario. The standard measurement of evapotranspiration was the energy balance method, using the Bowen ratio. The component fluxes of the energy balance were evaluated for ninety-seven hours on ten separate days. A comparison is made of two days with markedly different moisture availability to show how the magnitude of the component fluxes changed. Also the effect of the plant on the evaporative flux is examined. On days when water was non-limiting the model gave excellent results for hourly and daily totals: within 5% of measured evapotranspiration. When water became limiting the model overestimated by as much as 30%. It is further shown that the Penman model appears to be more sensitive to changes in the evaporative flux than the water equivalent of net radiation. The relationship of cumulative dry matter production of the crop and cumulative potential evapotranspiration was examined and was found to be linear for most of the field season, substantiating the hypothesis of Penman (1962).

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TABLE OF CONTENTS

Table of Contents - continued

LIST OF DIAGRAMS

List of Diagrams - continued

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION

Evaporation, in the plant environment, is basically a dual process consisting of direct evaporation from the soil or leaf surface, and the loss of water, by transpiration, through the stomata. These processes are combined under the term evapotranspiration (E_T). It is the passage of water through the plant which is of fundamental importance to the growth process, as water is an essential constituent in the formation of organic material in the living plant.

E_T can be regarded as a diffusion process in which water, in the vapour state, is transferred from a vegetated surface into the atmosphere. There are two basic requirements: an energy source to convert water to vapour, and turbulent air flow to transport vapour away from the surface. The bulk of the energy is provided by net radiation. Under certain conditions additional energy is provided by heat transfer from the air.

The evaluation of E_T for any vegetated surface requires rigorous instrumentation. This is seldom available, and climatologists have sought simpler approximations mainly through the concept of potential evapotranspiration (PE). As defined by Penman (1956), potential transpiration (his term for PE) is

> "the amount of water transpired, in unit time, by a short green crop, completely shading the ground, of uniform height and never short of water."

If water is limiting the evaporative loss may be less than PE and is usually thought of as the actual evapotranspiration (E_T). However, the terms E_T and PE are not mutually exclusive, because, under PE conditions, PE = E_T. The relation between the two is not clear when water is a limiting factor.

The aims of the study are threefold:

1) to determine a standard measurement of E_T, using the conservation of energy principle.

2) to estimate PE using a combination model (Penman 1948) and to test it against comparable E_T totals.

3) to test the hypothesis that cumulative crop productivity is related to cumulative PE totals.

The conservation of energy principle has been widely used for E_T, but it requires non-standard instrumentation. In order to avoid instrumental difficulties, Penman produced an approximation to give values of PE using commonly measured climatic parameters. The performance of this model has been very satisfactory. Tanner and Pelton (1960) found the model values to be within 5% of measured E_T over irrigated alfalfa for daily totals. Similar agreement has been found by Slatyer and McIlroy (1961) and van Bavel (1966) for hourly and daily totals.

The work reported here was carried out at the Ontario Department of Agriculture and Food, Horticultural Experiment Station, Simcoe, in

Norfolk County. An irrigated perennial ryegrass plot was used. It was seeded in late May, and a workable cover was obtained within six weeks. The field programme commenced on July 5, 1967 and finished on September 5, 1967.

CHAPTER TWO

THEORETICAL CONSIDERATIONS

1. Evapotranspiration from the energy balance equation

Following the conservation of energy principle, the energy balance equation, for any vegetated surface, in the absence of advected heat is

$$R_n = E_T + H + G + P \qquad (1)$$

where

R_n = net radiation (the difference between incoming and outgoing radiation fluxes irrespective of wavelength).

E_T = energy used in the evaporative flux into the air.

H = sensible heat flux into the air.

G = heat flux into the ground

P = energy used for photosynthesis.

Because the P term is usually very small, less than 5% of R_n, it can be ignored (Yocum, Allen and Lemon, 1964).

R_n and G can be measured directly, and, therefore, the problem is to partition $Rn - G$ between E_T and H. Since the direct measurement of either E_T or H is still in the developmental stage (Dyer, Hicks and King, 1967), other equations have to be incorporated. Aerodynamic theory states that the flux of any quantity, F, away for a surface, is proportional to the product of the vertical gradient ($\partial F/\partial z$) of the quantity, away from the surface, and an appropriate transport coefficient (K_F).

$$F = K_F \; \partial F/\partial z. \tag{2}$$

Replacing the differential form with finite differences, equation (2) becomes

$$F = K_F \; \Delta F/\Delta z. \tag{3}$$

For sensible and evaporative heat flux, this general form becomes

$$E_T = -\rho L K_w \; \Delta e/\Delta z \tag{3a}$$

and

$$H = -\rho C_p K_H \; \Delta T/\Delta z \tag{3b}$$

where ρ = air density (g cm^{-3})

K_w = eddy diffusivity for water vapour (cm^2 sec^{-1})

K_H = eddy conductivity for heat (cm^2 sec^{-1})

T = temperature (°C). (Ideally, T should be the potential temperature to correct for the adiabatic lapse rate)

L = latent heat of vapourisation (cal g^{-1} water)

e = vapour pressure (mb)

C_p = specific heat of air at constant pressure (cal g^{-1} deg^{-1}).

From equation (1)

$$R_n - G = E_T + H, \qquad (4)$$

or
$$R_n - G = E_T\,(1 + H/E_T)$$

Hence,
$$E_T = \frac{R_n - G}{(1 + H/E_T)} \qquad (5)$$

where

$$H/E_T = \beta\text{, the Bowen ratio (Bowen, 1926).}$$

From equations (3a) and (3b),

$$H/E_T = \frac{\gamma K_H \;\Delta T/\Delta z}{K_w \;\Delta e/\Delta z}$$

where $\gamma = Cp/L = 0.66\ °C^{-1}\ mb^{-1}$

If Δ z refers to the same height interval in each case, and since $K_H = K_w$ (Swinbank and Dyer, 1967 and Dyer, 1967),

$$E_T = \frac{R_n - G}{1 + \dfrac{\gamma\,(T_1 - T_2)}{(e_1 - e_2)}} \qquad (6)$$

where the subscripts 1 and 2 refer to a lower and upper level of measurement.

The evaluation of evapotranspiration using the Bowen ratio requires two-level measurement of temperature and humidity, above the surface, in addition to net radiation and soil heat flux.

2. Potential evapotranspiration from the Penman model

Penman (1948) sought to overcome the need for two-level measurement to solve the Bowen ratio. He combined the energy balance with aerodynamic equations to determine initially open water evaporation which could then be converted to PE over land surfaces. In more recent work (Penman, Angus and van Bavel, 1967) PE is obtained directly. He used the following aerodynamic equations:

$$E_T = f\,(u)\quad (e_s - e_a), \tag{7}$$

and

$$H = \gamma\, f(u)\quad (T_s - T_a), \tag{8}$$

where f(u) is an empirical wind function and subscripts s and a refer to the surface and screen height.

These equations are combined, as in the Bowen ratio, to give

$$\beta = H/E_T = \frac{\gamma\,(T_s - T_a)}{(e_s - e_a)}\quad , \tag{9}$$

thence

$$H = E_T\quad \frac{\gamma\,(T_s - T_a)}{(e_s - e_a)}\quad , \tag{10}$$

or

$$H = E_T\quad \frac{\gamma\,\Delta\,T}{\Delta\,e}\quad , \tag{11}$$

Substituting equation (11) into equation (4)

$$R_n - G = E_T + E_T\ \frac{\gamma\,\Delta\,T}{\Delta\,e} \tag{12}$$

To avoid the need for the measurement of Δ T and Δ e, Penman uses an approximation. If the slope of the saturation vapour pressure - air temperature curve is Δ, $\Delta e/\Delta T = \Delta$, and $\Delta T/\Delta e = 1/\Delta$.

Equation (12) becomes

$$R_n - G = E_T + E_T \gamma/\Delta \qquad (13)$$

Introducing the aerodynamic expression for E_T (equation 7),

$$R_n - G = E_T + \gamma/\Delta \, . \, f(u) \, (e_s - e_a) \qquad (14)$$

Equation (14) contains the unmeasurable quantity e_s, and, therefore, Penman approximates by introducing the saturation deficit at air temperature. He subtracts e_s and e_a from the saturation vapour pressure at air temperature (e_d). Thus,

$$R_n - G = E_T + \gamma/\Delta \, f(u) \, [(e_d - e_s) - (e_d - e_a)]$$

or

$$R_n - G = E_T + \gamma/\Delta \, f(u) \, (e_d - e_s) - \gamma/\Delta \, f(u) \, (e_d - e_a). \qquad (15)$$

Defining E_T as $f(u) \, (e_d - e_s)$

and E_a as $f(u) \, (e_d - e_a)$, equation (15) becomes

$$R_n - G = E_T + \gamma/\Delta \, E_T - \gamma/\Delta \, E_a. \qquad (16)$$

After rearranging,

$$E_T + \gamma/\Delta \, E_T = R_n - G + \gamma/\Delta \, E_a,$$

and

$$E_T (1 + \gamma/\Delta) = (R_n - G) + \gamma/\Delta\ E_a.$$

Therefore,

$$E_T = \frac{(R_n - G) + \gamma/\Delta\ E_a}{1 + \gamma/\Delta}, \tag{17}$$

or

$$E_T = \frac{\Delta/\gamma\ (R_n - G) + E_a}{\Delta/\gamma + 1}. \tag{18}$$

Equation (18) gives values of E_T for a short green crop where water is not limiting. When Penman tested the model, G was ignored, and R_n was approximated from a series of empirical equations.

Originally, Penman defined the wind function term, E_a, as

$$E_a = 0.35\ (1 + u/100)\ (e_d - e_a), \tag{19}$$

where

$$u = \text{wind run at 2 m. in miles day}^{-1}.$$

This equation clearly does not consider differences in surface roughness of vegetated surfaces. Tanner and Pelton (1960), working over irrigated alfalfa, found the E_a term to be inadequate. When it was replaced with the Businger wind function (Businger, 1956), the model gave excellent results. This wind function incorporates surface roughness. It is

$$f(u) = u.\ 1.2\ [k^{-1} \ln\ (Z + Z_o) / Z_o]^{-2} \tag{20}$$

where

k = von Karman's constant (0.4)

Z = height of anemometer (170 cm)

Z_o = a crop roughness parameter, (cm)

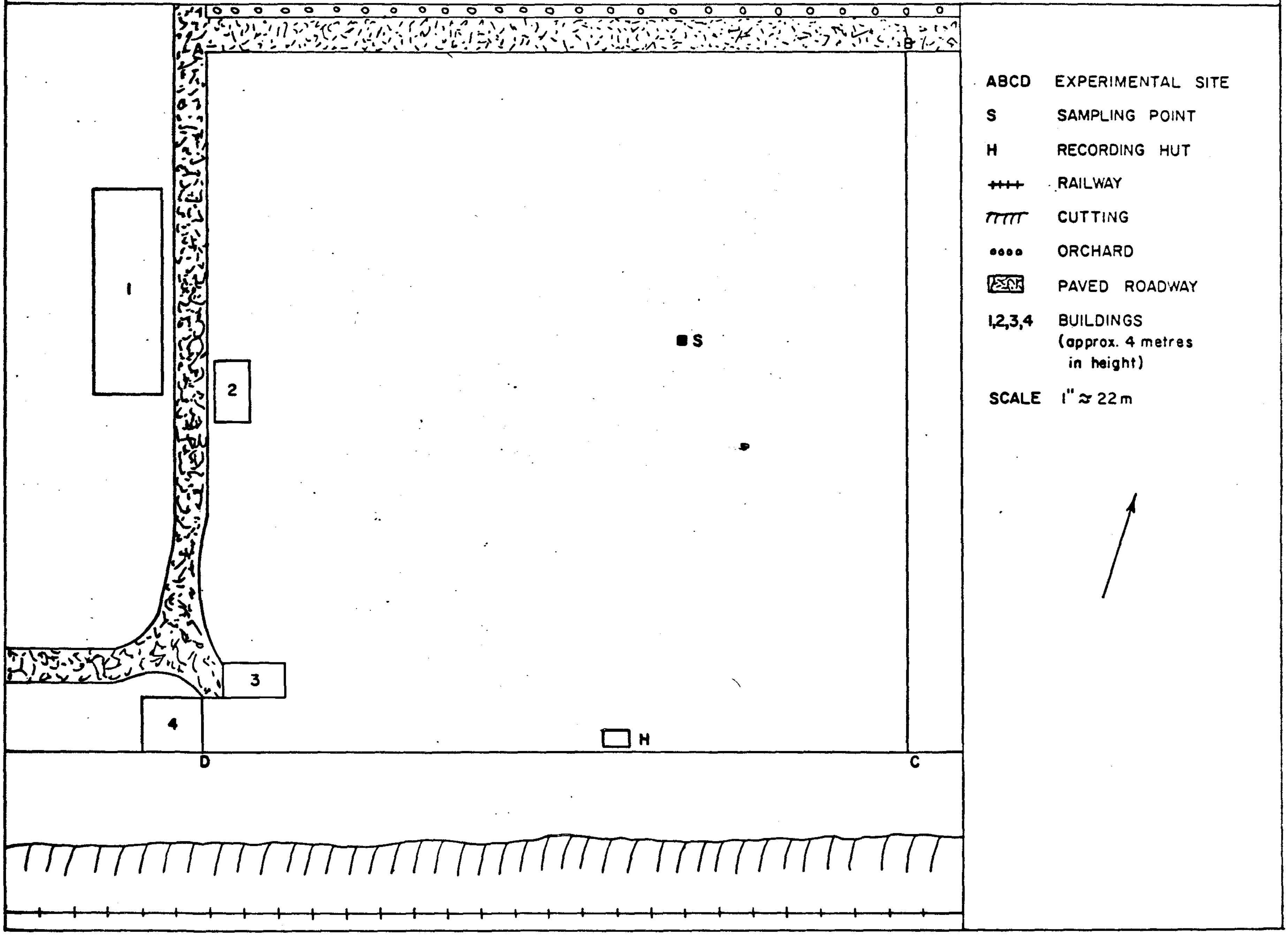
Z_o is the intercept on the height axis obtained from a line of best fit to a plot of wind speed (x axis) against the logarithm of height (y axis), for the wind profile.

3. Crop productivity

Within the field of crop weather relations, it would be beneficial to have a parameter which is simply related to productivity. Productivity, in this context, is interpreted as meaning dry matter accumulation in the plant. Penman (1962) hypothesized that productivity is linearly related to PE totals. This hypothesis was substantiated using a grass crop. One conclusion drawn was that, under PE conditions, the maximum productivity of the crop obtained. This is significant in irrigation agriculture, and it merits testing under different field conditions.

EXPERIMENTAL SITE

FIG. 1



CHAPTER THREE

EXPERIMENTAL SITE AND METHOD

1. Site

The observations were carried out on a flat rectangular plot, of perennial ryegrass 122 m x 102 m. To the east, the land sloped sharply towards a wood, 200 m away. A railway cutting defined the southern boundary, and an orchard defined the northern boundary. The western boundary was comparatively open except for three low buildings (Figure 1).

During the observational programme, it became apparent that the configuration of the land, around the site was influencing vertical winds at the sampling point. When the wind blew from certain directions, downdraughts were predominant, even under conditions of strong surface heating when updraughts were expected. These were probably produced by standing waves generated by adjacent topographical irregularities (Hare, unpublished manuscript). These results (Figure 2) show that, when the wind was from the west, updraughts were predominant during daytime surface heating and indicate that this was the most open side.

When profile measurements are taken above a surface, it is important to ensure that they are representative of that surface and in no way conditioned by upwind characteristics. For measurements to be

FIG 2

MEAN VERTICAL AND HORIZONTAL WIND COMPONENTS

July		0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
5	VERTICAL	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	
	DIRECTION	↘	→↘	→↘	↘	↘	↓↘	→	↘	→↘	↓↘	o	↖	
13	VERTICAL	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	
	DIRECTION	↓↘	↘	↘	↘	↘	↓	→↘	→↘	↘	→↘	→	→	
18	VERTICAL					↓	↓	↓	↓	↓	↓	↓	↓	↓
	DIRECTION					↑↗	↑↗	↗	↗	↗→	↗	↗	↑	↗
20	VERTICAL		↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
	DIRECTION		↖	↖	↖	↖↑	↖↑	↖	↗	↗	↖	↑	↗	↗
25	VERTICAL			↓	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓
	DIRECTION			→↘	→↘	↘	→↘	↘	↘	↘	→↘	↘	↘	↘
27	VERTICAL			↓	↓	↓	↓	↓	↓					
	DIRECTION			→	↗→	↗	↗	→	↗					

representative, they must be taken within the boundary layer: the surface layer of atmosphere, in which the gradients only reflect the influence of the underlying surface and in which vertical fluxes are constant with height. The height of the boundary layer grows with distance (fetch) from the leading edge (the point where surface characteristics change). The variation of fetch in this experiment is shown in Figure 3 .

The only height fetch relationship in the literature was presented by Elliott (1958). He defines the relationship as:

$$h = 0.75X^{0.8} \cdot Zo^{0.2}, \tag{21}$$

where h = height of the boundary layer (cm)

X = fetch distance (m)

Zo = roughness length (cm)

This relationship was applied to the experimental site using the maximum and minimum fetch distances and an average Zo value of 2.0 cm. The results are shown below.

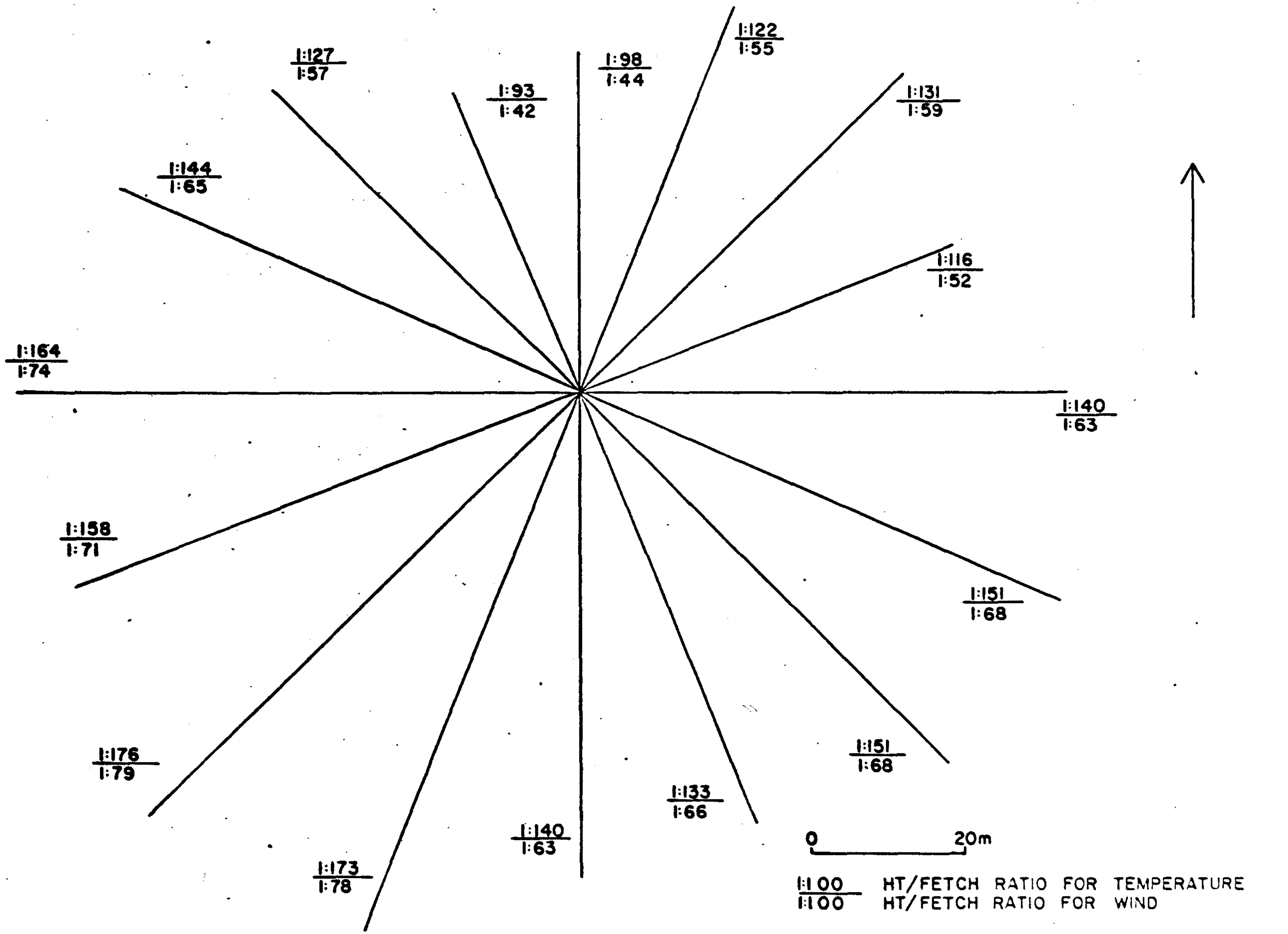
Fetch (m)	h (cm)
42	17
79	28

Since the highest sampling point for temperature and humidity gradient measurement was 45 cm, these measurements were never within the boundary layer, according to equation (21).

There is little standardisation of views on fetch requirements. The commonest way of treating the relationship between the maximum height

Fig. 3

VARIATION OF FETCH



of measurement for representative profiles and the fetch distance is by using rule-of-thumb height/fetch ratios. Lettau (1959) states that the ratio should not be less than 1:50, while Slatyer and McIlroy (1961) recommend a value of 1:100. Due to the conflict of views it has been stated by Penman, Angus and van Bavel (1967) that, "local rules based on local research may be the only solution."

In this experiment the height/fetch ratio varied from 1:93 to 1:176 for temperature and humidity gradient measurement. In wind profile measurement the highest anemometer was at 1 m and therefore the ratio varied from 1:42 to 1:79. The sampling point was selected to give the longest fetch in the prevailing wind direction, between south and west.

A test of the adequacy of the fetch can be made using wind profile data. If wind profile measurements are made within the boundary layer, in neutral conditions, windspeed will vary linearly with the logarithm of the height. On days when temperature gradients were measured in conjunction with wind gradients[1], the wind profiles, under neutral conditions were plotted. The air is neutral when the environmental lapse rate is equal to the dry adiabatic lapse rate (1°C/100 m). Over a height interval of 30 cm (the difference in height between the upper and lower temperature sensors) the dry adiabatic lapse rate would result in a temperature drop of 0.003°C. Therefore when $\Delta T \rightarrow 0$ the air was considered neutral.

---

1 On August 17 the energy balance was evaluated but no wind profile measurements were made due to instrumental failure.

Some of these profiles are shown in Figure 4. They show that the logarithmic wind law was applicable. These data were chosen because they represent days when the air was adjusting over the maximum fetch (July 18) and the minimum fetch (August 11). Therefore it can be assumed that the fetch was adequate for representative profiles of temperature, humidity and wind.

At the sampling point, an 8 m aluminium mast (C. W. Thornthwaite Associates) was erected (Plate 1). The temperature, humidity and wind sensors were attached to the mast using height adjustable cross-arms. The instrument hut, housing recording equipment, was situated on the southern boundary of the plot, 60 m from the sampling point.

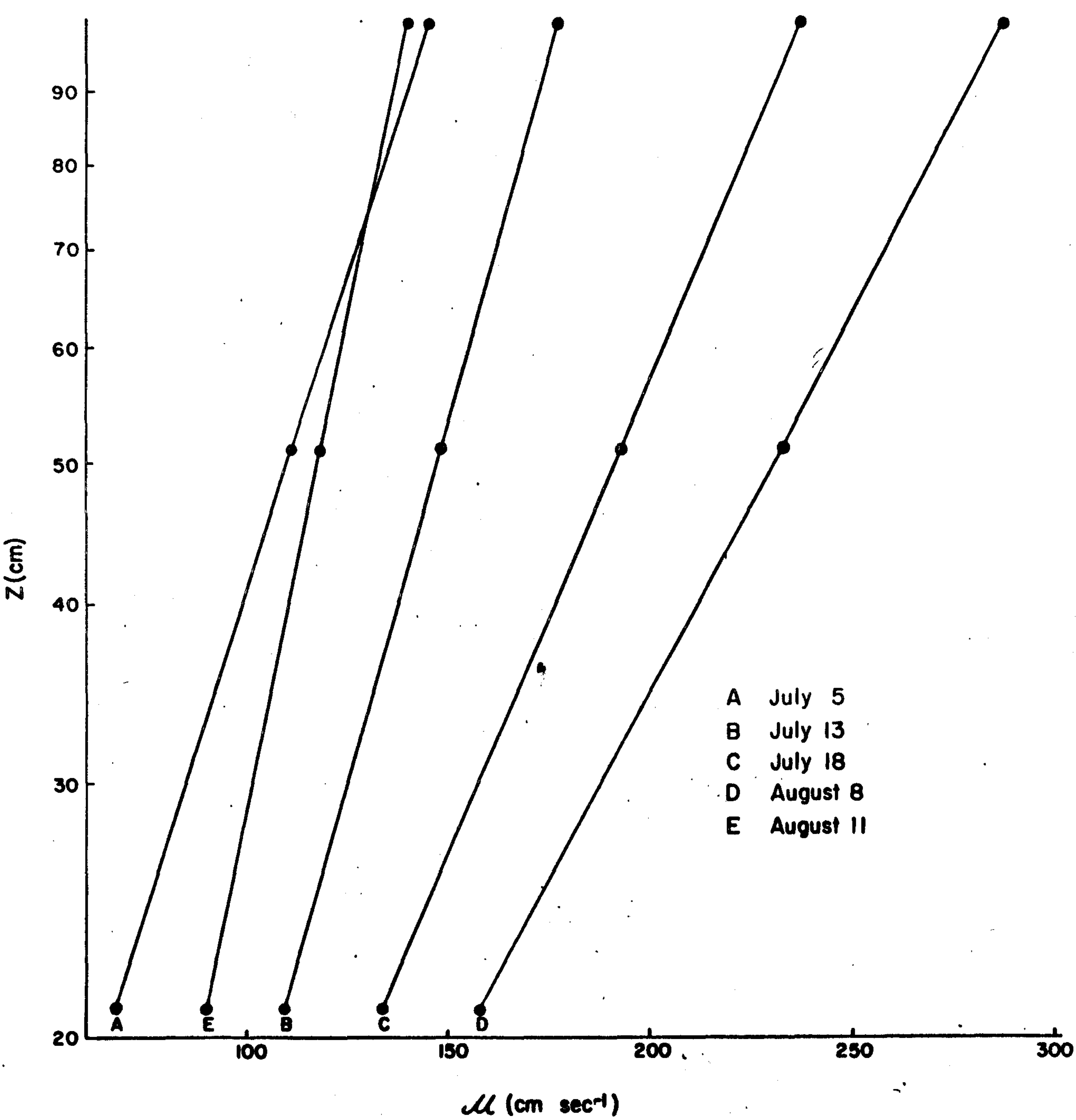
The soil in the area was a fine sandy loam which became almost pure sand at a depth of one metre. It exhibited excellent drainage characteristics and a low moisture retention capacity. To maintain field capacity, the plot received weekly sprinkler irrigation throughout most of the season. It was hoped that by this means the evapotranspiration was kept at the potential rate for most of the season (see chapter IV).

The quality of the surface cover was disappointing. At best, the perennial ryegrass attained a 75% ground cover, and, in places, this fell to as low as 50%. In addition, the stand was not completely pure, since it was invaded by barnyard grass. The poor quality of the surface is important in the interpretation of the results.

Each week, up to August 16, the site was cut with gang-mowers to a constant height of 4 cm. This corresponded to the height of the

Fig. 4

SAMPLE WIND PROFILES



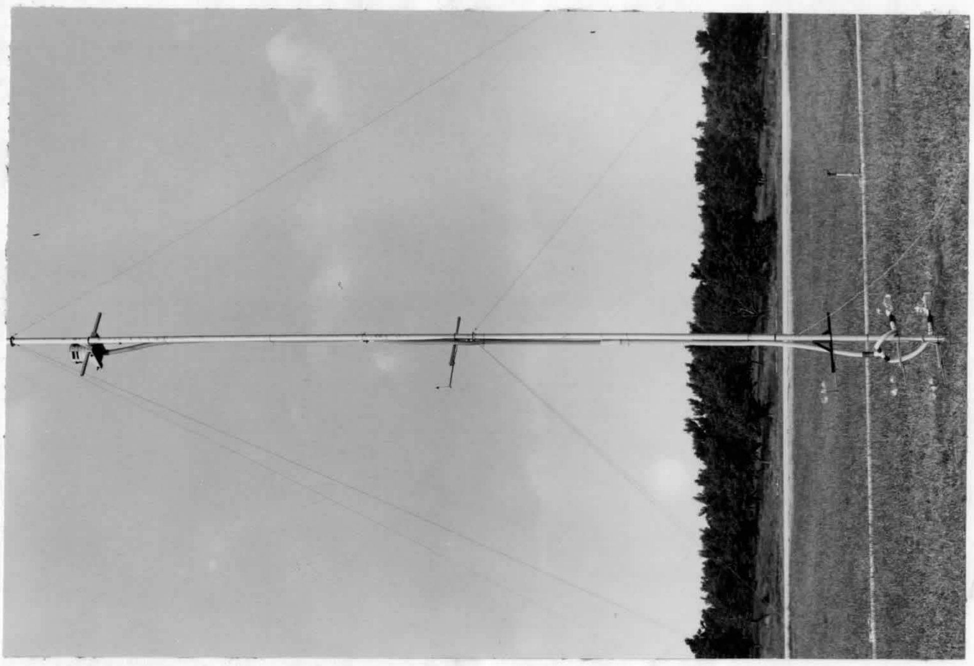


Plate 1. Thornthwaite mast

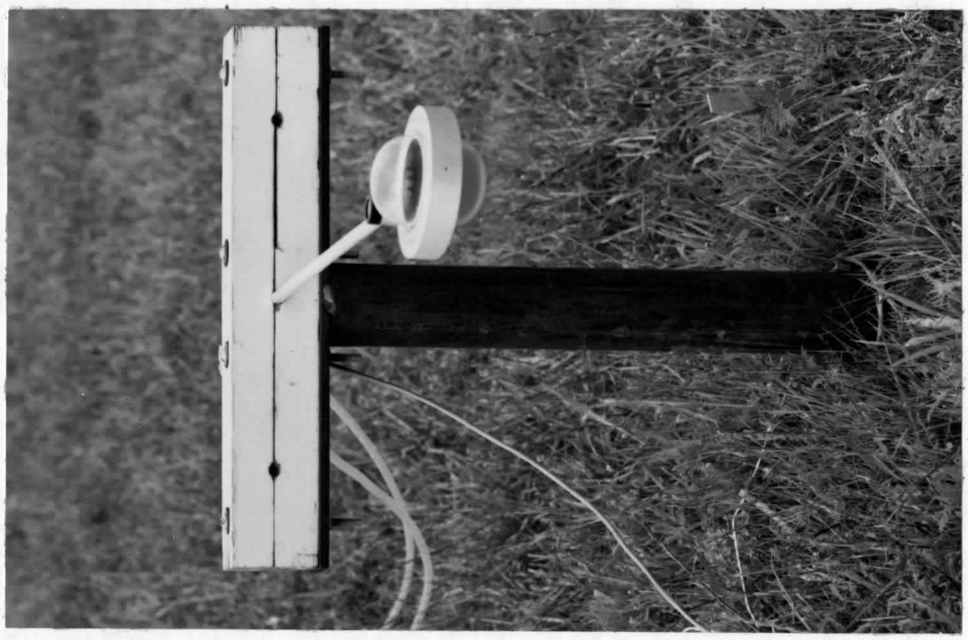


Plate 2. Swissteco ventilated net radiometer

quadrat used in productivity sampling. Normally, the cutting and irrigation of the site were performed on the same day, but sometimes, because of organizational problems, this was impossible, (see Figure 5).

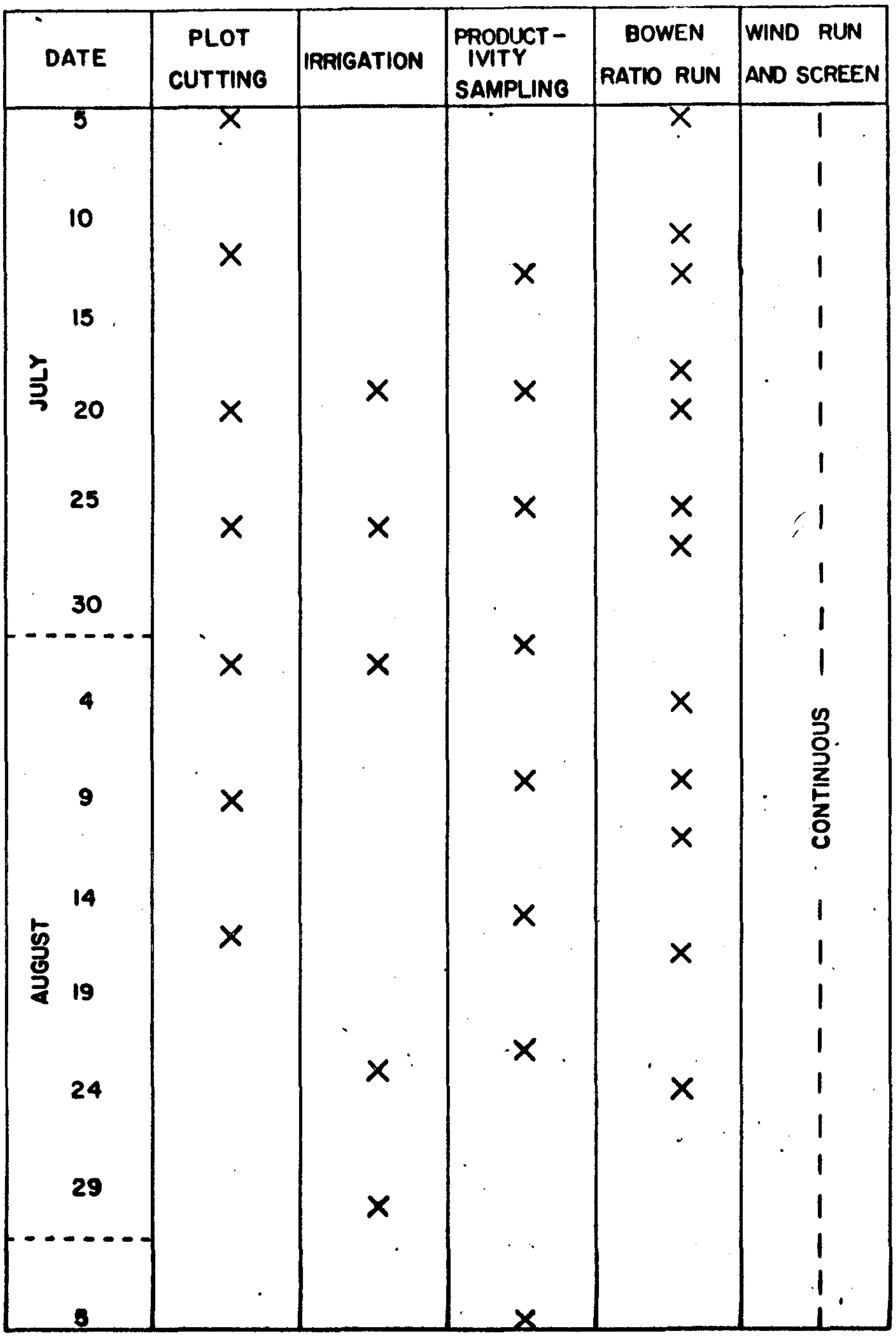
2. Measurement

Net radiation

Net radiation is the largest term in the energy balance equation, and error in its measurement will be reflected in the computed values of E_T. Net radiation was measured using a Funk net radiometer (Swissteco, Type S - 1). This instrument is a refined design of the original Funk net radiometer (Funk 1959). It was mounted at 0.5 m over a representative section of the surface (Plate 2). The thermopile surfaces were protected by polyethylene domes which were kept firm by the injection of a continuous stream of nitrogen. The gas was led from a cylinder, via tygon tubing, to the sensor and back from an exit port to a water-filled test tube. The rate of gas flow was determined from the bubble rate through the water. The manufacturers recommended a bubble rate of 15 to 20 min^{-1} to prevent condensation within the domes. This was found to be insufficient, and an average rate of 50 to 60 min^{-1} was maintained throughout the season. The output of the instrument (106.39 mv cal^{-1}) was recorded continuously on a 24-point electronic recorder (Esterline - Angus, Type - E 1124E). Since there was only one input, 23 channels were wired so that the instrument signal was received continuously, except for one channel which was shorted to define a zero line and to give a zero check. The integrated total of R_n for each day was found by planimetry.

Fig. 5

SCHEDULE OF SITE OPERATIONS



Temperature and humidity gradients

For evaluation of the Bowen ratio, temperature and humidity gradients were taken between 15 cm and 45 cm. Dry-bulb and wet-bulb thermocouples (16 a.w.g. Cu/constantan) were used. This wire has a limit of error of $\pm$ 0.83°C between -59°C and 149°C. Over a length of 60 m, the total resistance of this cable is 30 ohms, which is within the limit for the recording system used. The thermocouple junctions were butt-welded and soldered to increase their strength. The dry-bulbs were completely sealed with epoxy resin to prevent corrosion of the junction and moisture seepage along the wire under the polyvinyl coating. The wet-bulb junctions were sealed with epoxy resin at the base, but the remainder was left bare. This was to enhance moisture travel along the muslin wrapping. It is important to ensure that the wrapping of the wet bulb is clean to allow the free flow of water over the sensor (Slatyer and McIlroy, 1961). Before wrapping, the wick was dipped into a mild detergent solution, and handling was kept to a minimum.

Because the sensors were large, radiation shields were necessary (Fuchs and Tanner, 1965). Plate 3 shows the mounting arrangement of the shields, on the mast. Each shield consisted of an inner plastic tube, coated inside and out with aluminized tape (Mylar). The tube was enclosed in a styrofoam layer, which was also covered by Mylar tape. Since the tape has a high reflectivity and emissivity, and since styrofoam is a poor heat conductor, radiant heating was minimized. A small plastic bottle

Plate 3. Mounting arrangement of radiation shields

encased in styrofoam and covered in Mylar tape acted as a reservoir of distilled water which was led under gravity feed, through fine plastic tubing, to the wet-bulb sensor. The water feed was not completely satisfactory, and it required frequent attention in the field. Initially, the feed was too fast, but this was rectified by leading the wick through the feed tube half way to the reservoir. With this arrangement, a satisfactory rate was established.

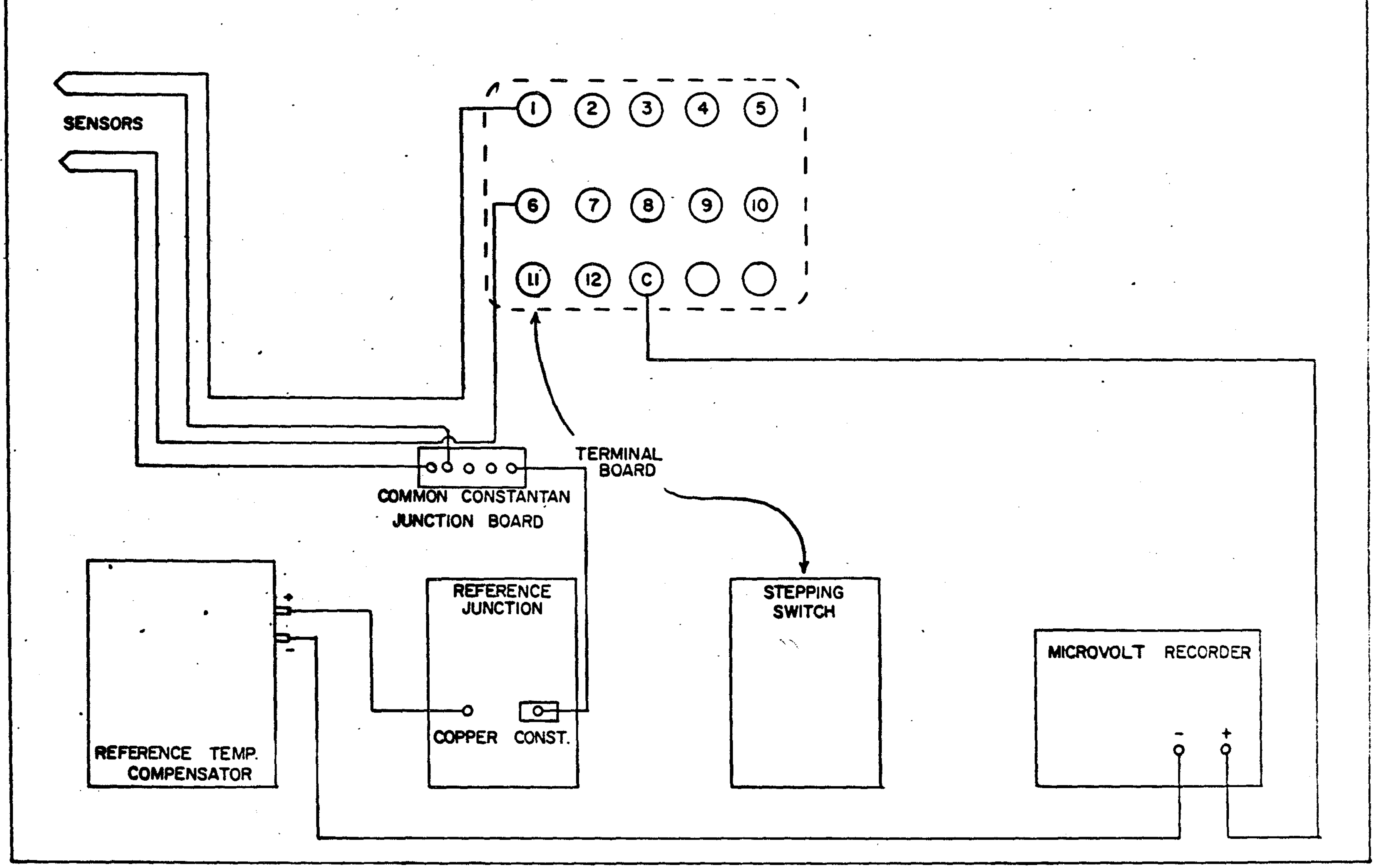
To ensure equilibrium between ambient air temperature and the sensor, the system was aspirated with a standard vacuum motor, mounted on top of the mast. The speed of the motor was regulated by a variable transformer. It was found that between 70 and 80 volts was sufficient to obtain complete wet-bulb depression.

The signals from the temperature and humidity sensors were recorded on two temperature recording systems (C. W. Thornthwaite Associates). The dry-bulb readings were sequentially recorded on one and the wet-bulbs on the other. Each system consists of a microvolt recorder, constant temperature reference bath, stepping switch and a reference temperature compensator (Figure 6).

The calibration of the wire with each reference temperature bath was carried out in the laboratory over a temperature range of +5° C to +25° C, using a portable potentiometer (Doran, U.K.). For each calibration, approximately 30 readings were taken. A regression analysis gave the equation of the line of best fit and the range of the standard error of y (temperature): 0.130° C to 1.229° C.

Fig. 6

TEMPERATURE RECORDING SYSTEM



This margin of error was disappointing, but the calibration thermometer read to only 0.1° C, and, together with human error, this would account for part of the high standard errors.

Wind profile

The only wind profile parameter used was Z_o. This was found from a three level wind system (C. W. Thornthwaite Associates). The sensitive anemometers were mounted at 20, 50 and 100 cm above the ground surface. The outputs from each anemometer were recorded on digital counters situated 30 m from the mast.

Soil heat flux

Soil heat flux was measured with two heat flow plates (C. W. Thornthwaite Associates), and eleven Deacon heat flow plates (Deacon, 1950). All plates were inserted at a depth of 2 cm. The Thornthwaite plates were inserted singly, close to the sampling point for net radiation. Six Deacon plates were connected in series and inserted in the north-west sector of the plot. The remaining five plates were similarly inserted in the south-east sector.

Parameters for the evaluation of the Penman equation

Wind run was measured, in miles day^{-1}, with a Casella cup counter anemometer, mounted at 1.7 m above the surface. This instrument is accurate over a windspeed range between 1 and 60 m p h. Dry-bulb and wet-bulb temperatures were taken with a conventional thermometer arrangement in an unventilated Stevenson Screen which was oriented, as was recommended, with the door facing north.

Frequency

Net radiation was recorded continuously for the complete field season. Data for the daily evaluation of the Penman equation were collected. These consisted of the wind run and at least three recordings of wet-bulb and dry-bulb screen temperatures. On selected days, concentrated runs were carried out. On such days, temperature, humidity and wind gradients were taken every ten minutes.[2] Soil heat flux, wind-run and screen temperature and humidity were taken on the hour.

Productivity

Productivity in this context is interpreted as the dry matter accumulation in the plant, excluding roots. Two plots, 6 m x 6 m, were chosen as representative of the site. These were widely separated; one in the north-west sector, and the other in the south-east sector of the site. In each plot, four 1 foot square plots were selected. This gave a 2% sample of ryegrass growth. Because of the mixed nature of the cover, it was necessary to weed each plot of species other than ryegrass, since the productivity of barnyard grass or other weeds was not relevant. Each week, the plots were sampled. This involved the laying of a 1 foot quadrat on each plot and cutting the grass flush with the top of the sides. The cuttings were transferred to an oven where they were dried at 105°C for 24 hours and then weighed to find dry matter accumulation. From August 8, 1967, the sample was increased to 3% when four extra sampling points were selected.

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[2] On certain days, wind profile measurements were taken every thirty minutes.

CHAPTER FOUR

RESULTS

1. Energy balance of perennial ryegrass

The components of the energy balance, photosynthesis being ignored, were evaluated for ninety-seven hours, on ten separate days (Appendix A). From the point readings of soil heat flux, it was apparent that it was always small. For this reason, it was treated as a constant: 5% of the net radiation. The energy used in the evaporative and sensible heat fluxes was then a residual, which was partitioned by the Bowen ratio method.

Temperature and humidity gradients

The evapotranspiration from a vegetated surface, with a plentiful supply of water, has been found by many workers to be a large fraction of the available energy. Under these conditions, the temperature gradients are small. In this study, this was true. Figure 7 shows that the dry-bulb temperature gradients were predominantly between 0.2°C and 0.6°C.[3] These figures suggest that most of the energy balance data were collected under potential evapotranspiration conditions. Throughout the observational period

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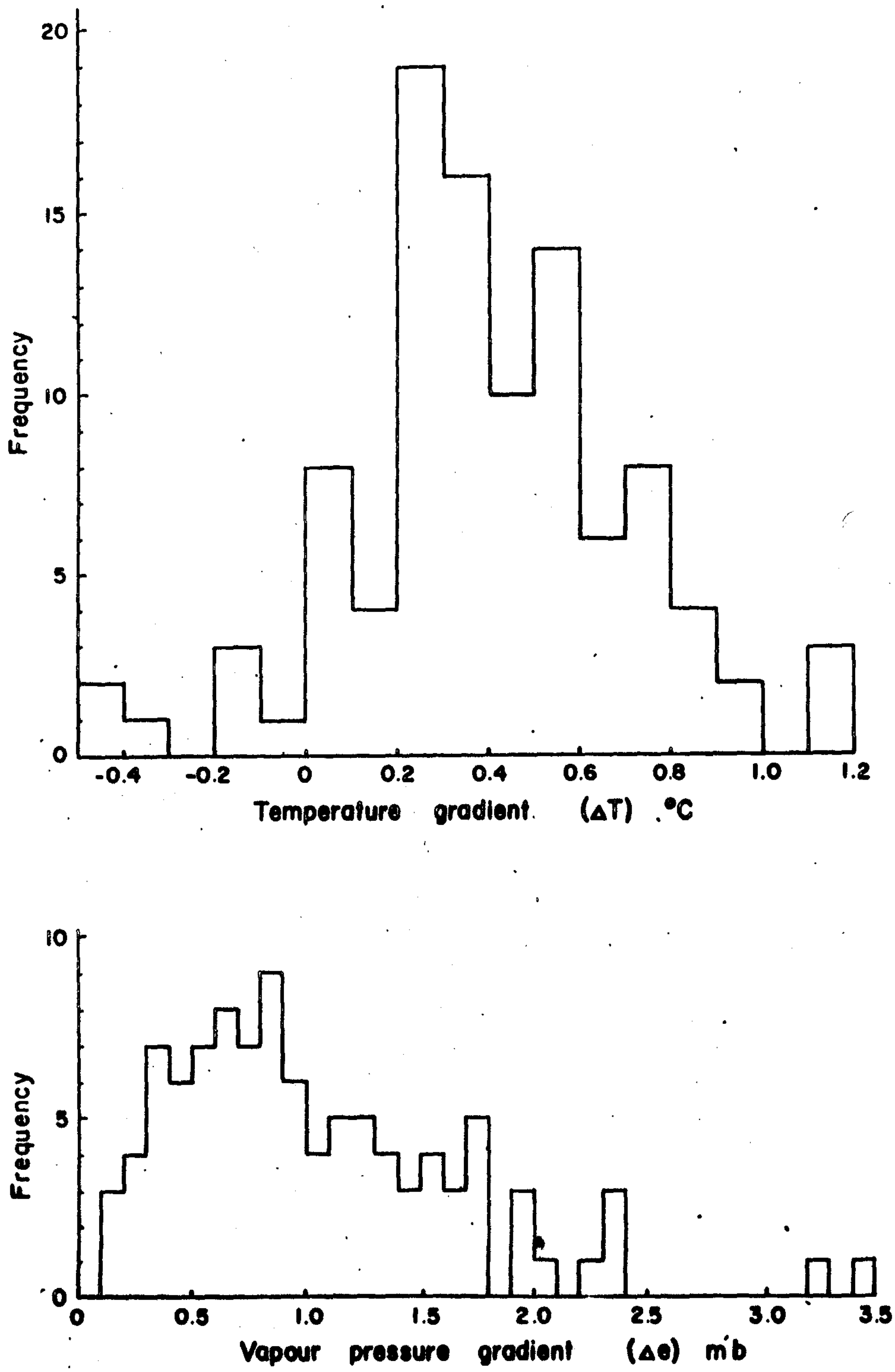
[3] There were only three hours when the hourly average temperature gradient exceeded 1°C.

Fig. 7

FREQUENCY DISTRIBUTIONS OF TEMPERATURE AND HUMIDITY GRADIENTS

(hourly averages)



it was not uncommon to find short-lived temperature inversions, under high radiation input, when lapse conditions were expected. A similar phenomenon was noted at Davis, California (Angus, 1963). He postulated that it was due to patches of warm and cool air moving with the general drift which occur most frequently under light-wind conditions. This indicates the presence of horizontal temperature gradients which are not accounted for by the one dimensional treatment of the Bowen ratio (Ch. 2). However, these conditions were relatively rare.

Tanner and Pelton (1960), working over a complete cover of irrigated alfalfa-brome, considered that PE conditions prevailed when the ratio of evapotranspiration to net radiation was $\geqslant 0.9$. Chang (1965) noted that several workers found values between 0.8 and 0.9. They included Graham and King (1961) for corn in Ontario, Harris and van Bavel (1958) for bermuda grass and sweet corn in N. Carolina, Gerber and Decker (1960) for corn in Missouri, Chang (1961) for sugar-cane in Hawaii, Scholte - Ubing (1959) for grass in the Netherlands and House, Rider and Tugwell (1960) for grass in England. Pruitt and Angus (1961) found a value of 0.85, as did Fritschen and van Bavel (1963) and Tanner and Lemon (1962). McIlroy and Angus (1964) found a value of 1.2 at Aspendale, Australia, but here, continental scale advection was operative.

In this study, the average daily ratio of evapotranspiration ($E_T l$) to net radiation ($\frac{Rn}{L}$), for the ten days, was 0.77. The daily ratios varied from 0.66 to 0.86 (Table 1).

TABLE 1

Daily ratios of $E_T 1/\frac{Rn}{L}$

Date	$E_T 1/\frac{Rn}{L}$
July 5 (before cutting)	0.73
July 5 (after cutting)	0.81
July 13	0.79
July 18	0.78
July 20	0.86
July 25	0.79
July 27	0.79
August 4	0.77
August 8	0.74
August 11	0.66
August 17	0.67

On six days the value lay between 0.75 and 0.80. On July 20, it was 0.86 which suggests that true potential evapotranspiration conditions were only encountered for one complete day. The concept of potential evapotranspiration assumes a complete vegetation cover which is freely transpiring. The ryegrass cover in this study was incomplete, and, the lower values found are consistent. On July 5, the grass was cut between 1200 and 1400 without any interruption to the data collection. It is significant that, after cutting, the average ratio increased from 0.73 to 0.81. This means that the cutting had a marked effect on the evaporative flux, and,

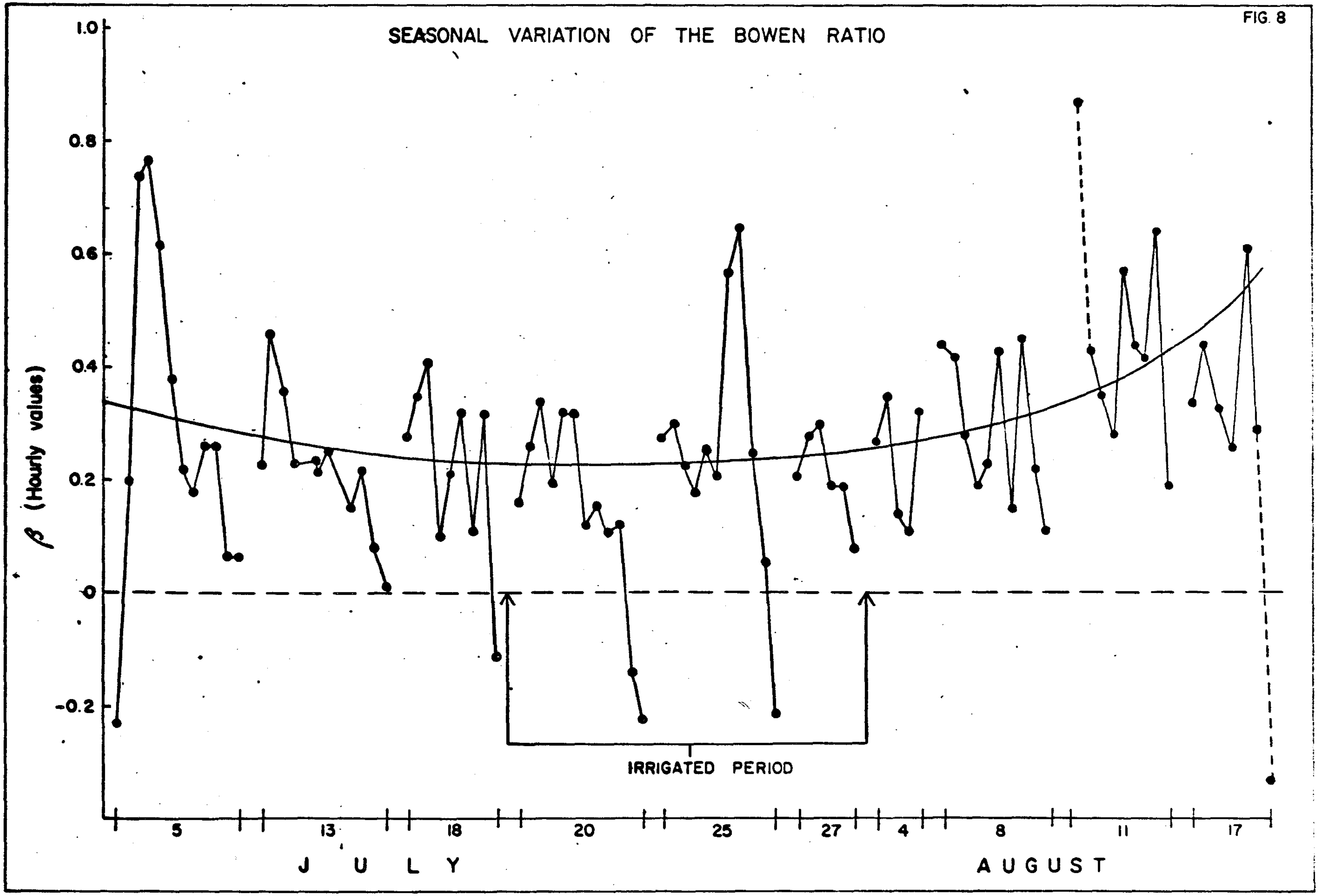


FIG. 8
SEASONAL VARIATION OF THE BOWEN RATIO
β (Hourly values)
1.0
0.8
0.6
0.4
0.2
0
-0.2
IRRIGATED PERIOD
5
13
18
20
25
27
4
8
11
17
J U L Y
A U G U S T

therefore, the morning and afternoon data will be treated separately.

Bowen ratio values

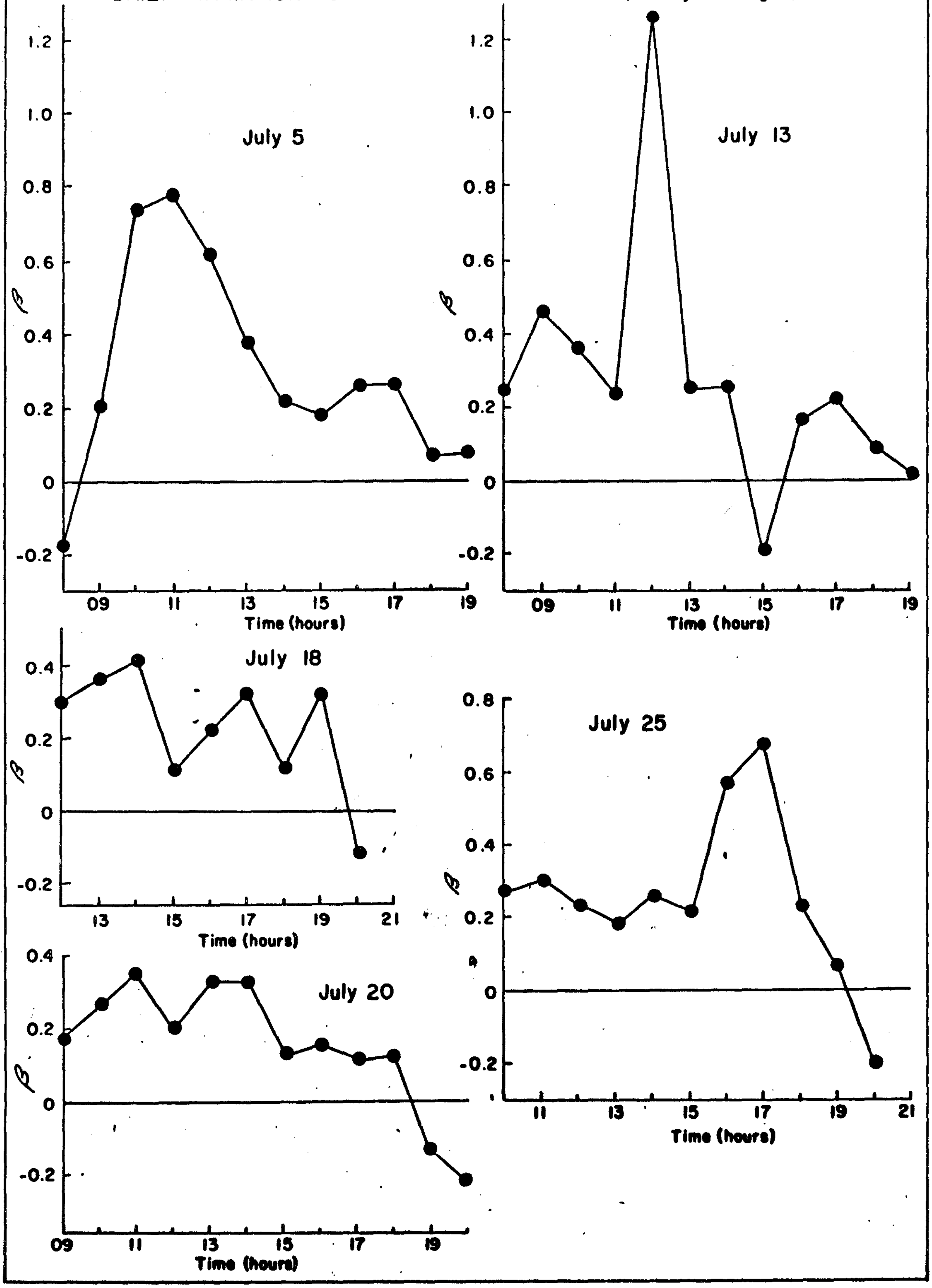
The variation of β for days throughout the season when energy balance runs were made is shown in Figure 8. All hourly values have been plotted, and the resulting irregular scatter was fitted by a curve drawn by eye. The fall-of of β during irrigation and its progressive rise as the surface dried towards the end of the season, is apparent. The general implication of this trend is that, during irrigation, water was more readily available for evaporation, and, thus, large temperature gradients did not develop. Hence, β was small and fairly constant. Figures 9 and 10 show separate scatters of β for eacy day and several unusual values deserve mention. At 1200 on July 13, β was abnormally large (1.26). At this time, the temperature gradient was large (1.2°C). However, since the recording of temperature was satisfactory for the whole season, this temperature value is probably correct. The corresponding humidity gradient was small (0.62 mb), and it is probable that at this time the water feed to one of the humidity sensors was inadequate. A similar situation and explanation is applicable for 1600 on August 17 (β = 1.58). It is also clear from these figures that β usually became negative between 1900 and 2000, which indicates the development of inversion conditions.

Selected days

Out of the ten days of data, four are selected for detailed study. These are July 20 and 25, and August 8 and 11. These days were selected

Fig. 9

DAILY VARIATION OF THE BOWEN RATIO (hourly averages)



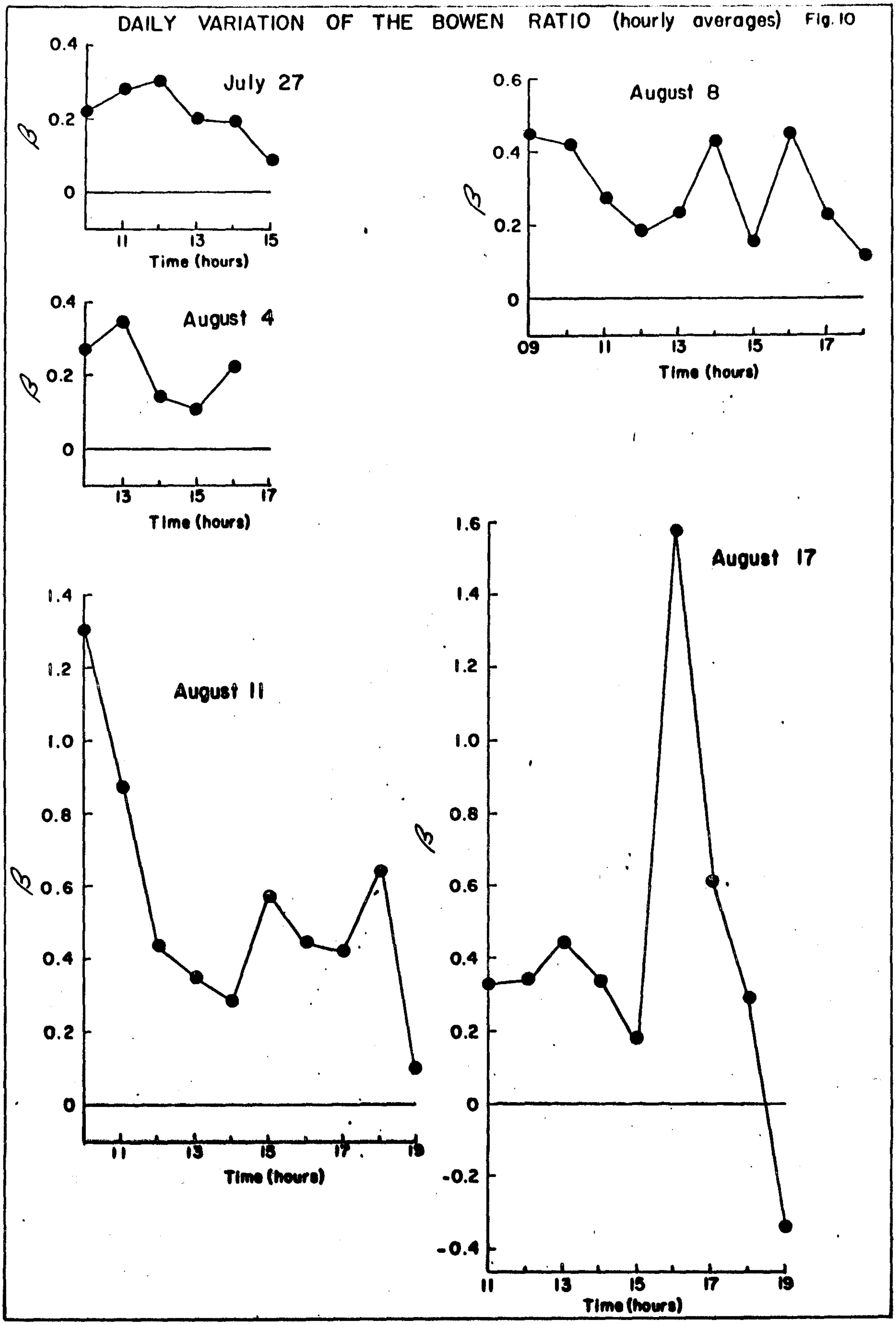

DAILY VARIATION OF THE BOWEN RATIO (hourly averages) Fig. 10
July 27
August 4
August 8
August 11
August 17
β
Time (hours)

TABLE 2

Rainfall, irrigation and cutting schedule

Date (Period-hours)	Rainfall in previous 7 days (mm)	Rainfall in previous 3 days (mm)	Irrigation	Plot Cutting
July 5 (12)	6.7	1.0	Absent	<0
July 13 (12)	17.5	8.6	Absent	<1
July 18 (9)	13.7	5.3	Absent	<6
July 20 (12)	5.3	0.0	<1 (i.e. one day previous)	<0
July 25 (11)	1.3	0.7	<6	<5
July 27 (6)	1.3	0.7	<1	<1
August 4 (5)	7.4	2.5	<2	<2
August 8 (10)	7.9	1.5	<6	<6
August 11 (10)	17.3	11.9	<9	<2
August 17 (9)	0.0	0.0	<15	<1

because the data were almost complete for the daylight period, and because the results demonstrate some of the effects of partial drying of the surface. The energy balance components for July 20 are shown in Figure 11. On this day the mean wind direction varied from south-west to south-east, therefore the height/fetch ratio varied from 1:133 to 1:176 (see Fig. 3); thus, the results can be considered to be typical of the surface. There was irrigation on the previous day, and in the previous week, there was 5.3 mm of rainfall (Table 2). The ratio of $E_T l / \frac{Rn}{L}$ averaged over the day, was 0.86. The positive net radiation total on this date was one of the highest for the season: 6.7 mm (see Fig. 12). The net radiation curve for this day is almost perfectly smooth due to cloudless conditions, except between 1000 and 1100. Between 1200 and 1500, the evaporation rate dropped off markedly, and sensible heat flux increased. There is no apparent meteorological or instrumental reason for this; hence, it is likely to be a plant factor. It is postulated that the phenomenon is due to partial stomatal closure under high levels of radiation. A further point of interest from this graph is the changeover between 1800 and 1900 to a positive sensible heat flux, with the development of a temperature inversion, and, therefore, negative β values.

On July 25, the mean hourly wind direction varied from west to north-west; hence, the height/fetch ratio varied from 1:127 to 1:164. Six days had elapsed since the last irrigation, and only 0.7 mm of rain had fallen in the period; hence, water input was minimal. The total evapotranspiration was 4.3 mm compared to 5.6 mm on July 20, and the ratio of

Fig. 11

ENERGY BALANCE COMPONENTS FOR JULY 20

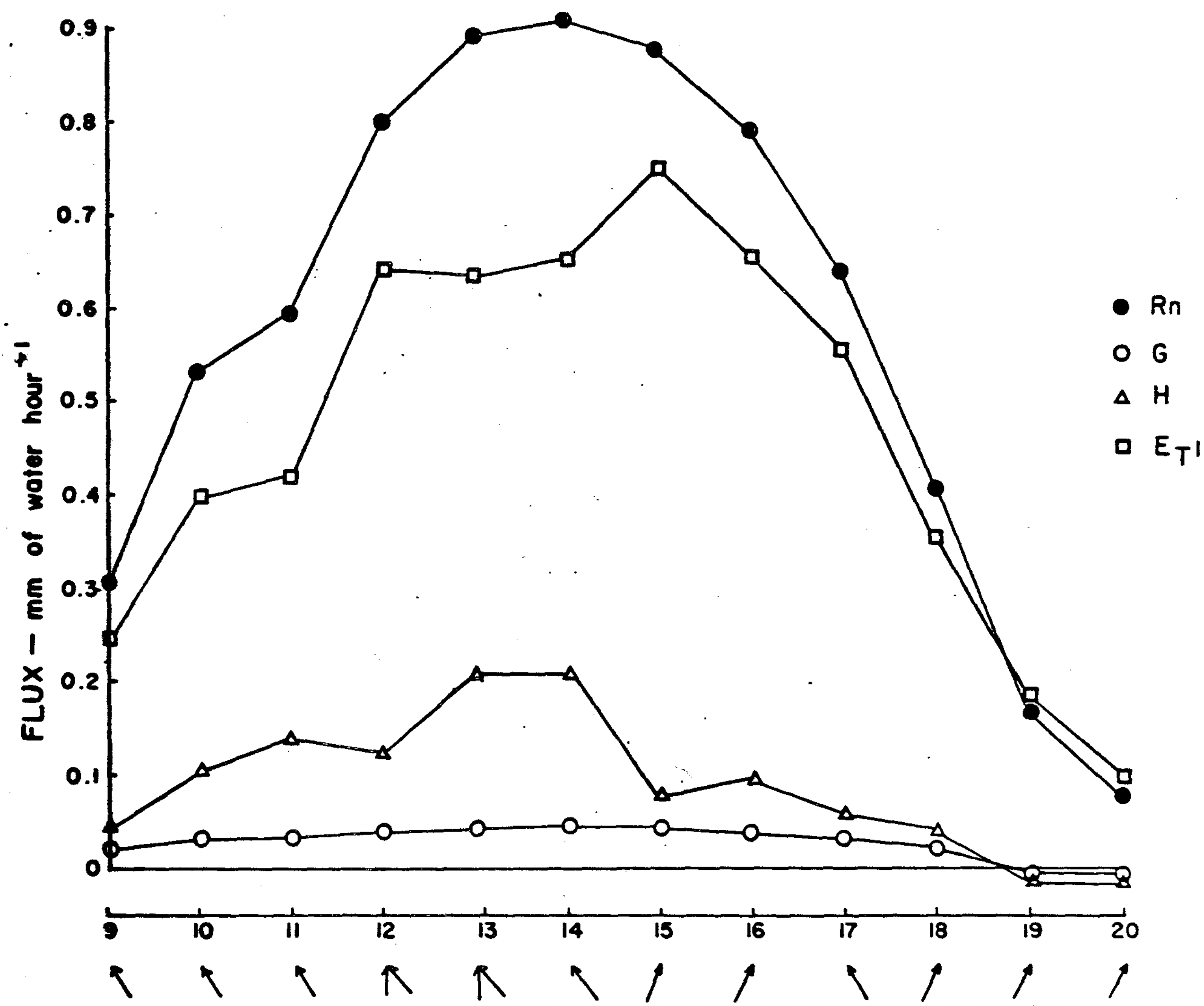
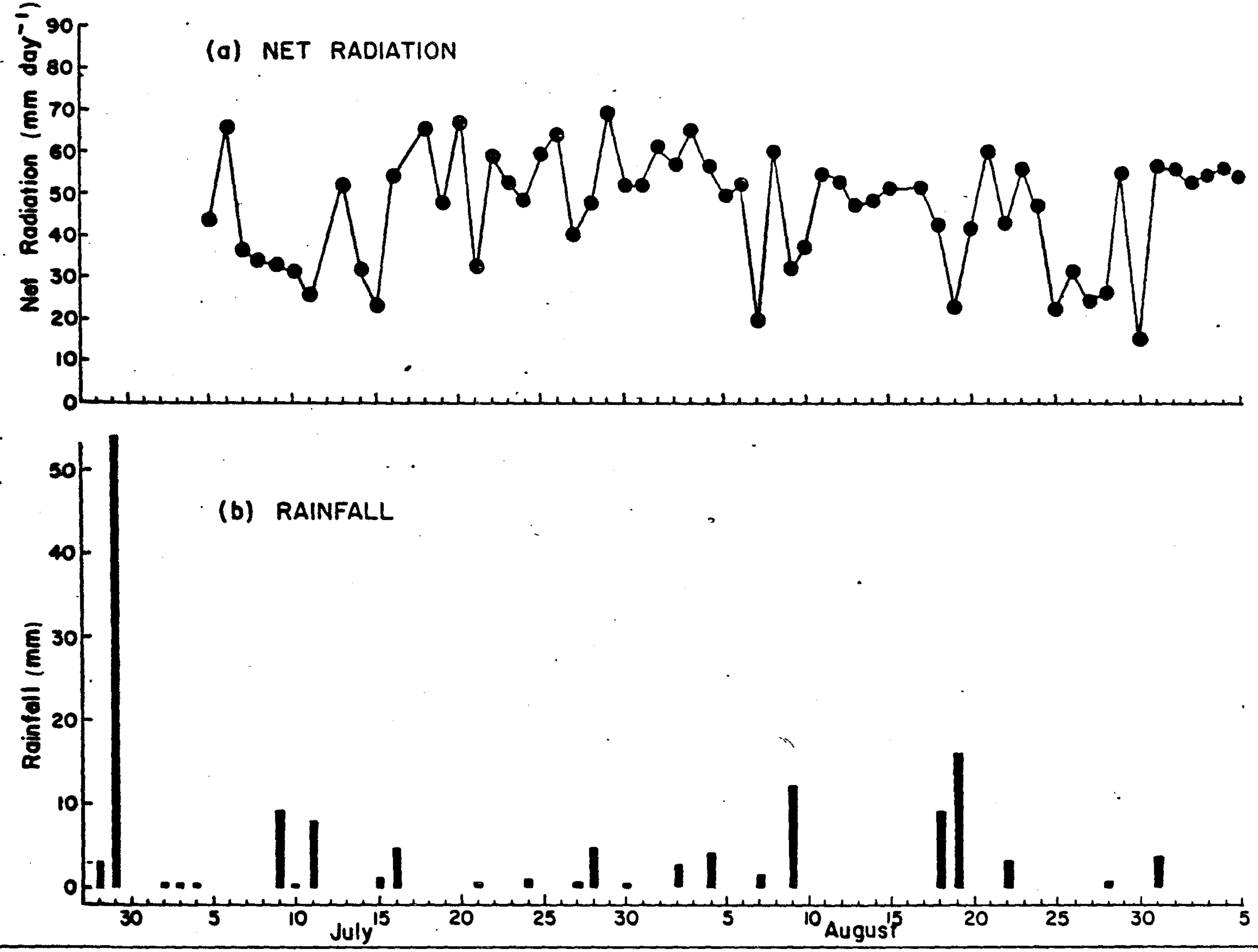


Fig. 12

NET RADIATION AND RAINFALL OVER THE EXPERIMENTAL PERIOD



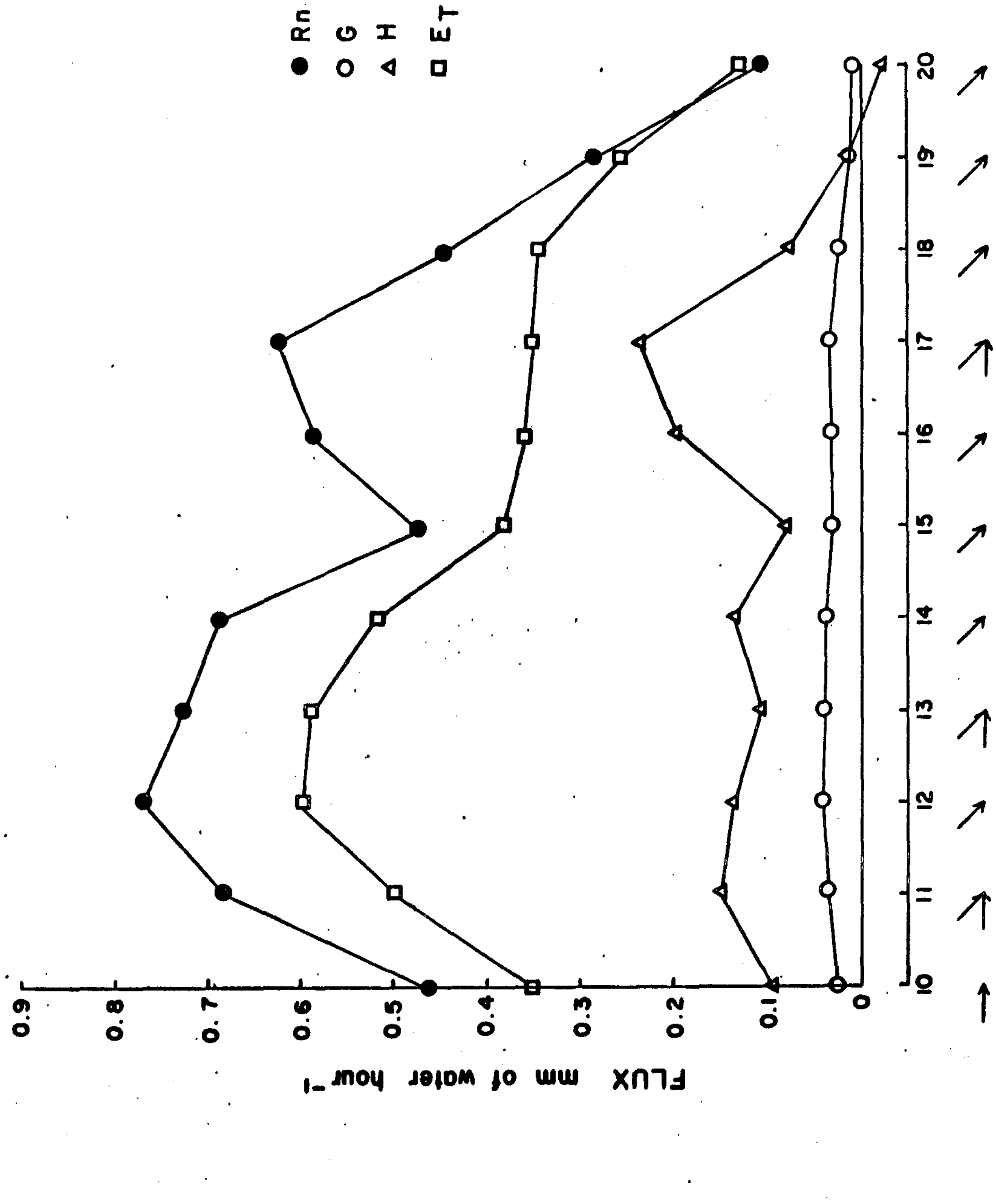
$E_T l/\frac{Rn}{L}$ fell from 0.86 to 0.79. These figures show that the surface was becoming progressively drier. Figure 13 shows the magnitude of the component fluxes. The marked drop in net radiation between 1400 and 1500 is due to clouds. When net radiation increased after 1500 hours, there is a significant rise in sensible heat flux up to 1800. This is probably due to the effect of partial stomatal closure. The rise in sensible heat flux occurred later on July 25 than on July 20, and the main reason is the difference is net radiation amount. On this day, the net radiation was lower than on July 20, and the postulated stomatal closure did not start until later in the day, when net radiation increased markedly.

August 8 is similar to July 25 in that six days had elapsed since irrigation. The mean hourly wind direction varied from north-west to south-west, so that the height/fetch ratio varied from 1:127 to 1:176. The ratio of $E_T l/\frac{Rn}{L}$ was 0.74. The total evapotranspiration was 4.6 mm. From Figure 14, a marked rise in sensible heat flux in the early afternoon is apparent. This, again may be due to partial stomatal closure. The large evapotranspiration amount between 1400 and 1500 is problematic. From an examination of the data, it was found that an abnormally large humidity gradient was associated with a relatively small temperature gradient. Field notes indicated difficulty with the water feed to the upper humidity sensor, and it is likely, therefore, that the computed evapotranspiration is too large.

On August 11, the height/fetch ratio varied from 1:93 to 1:131. The ratio of $E_T l/\frac{Rn}{L}$ was 0.66 compared to 0.74 on August 8. Thus, the surface

Fig. 13

ENERGY BALANCE COMPONENTS FOR JULY 25



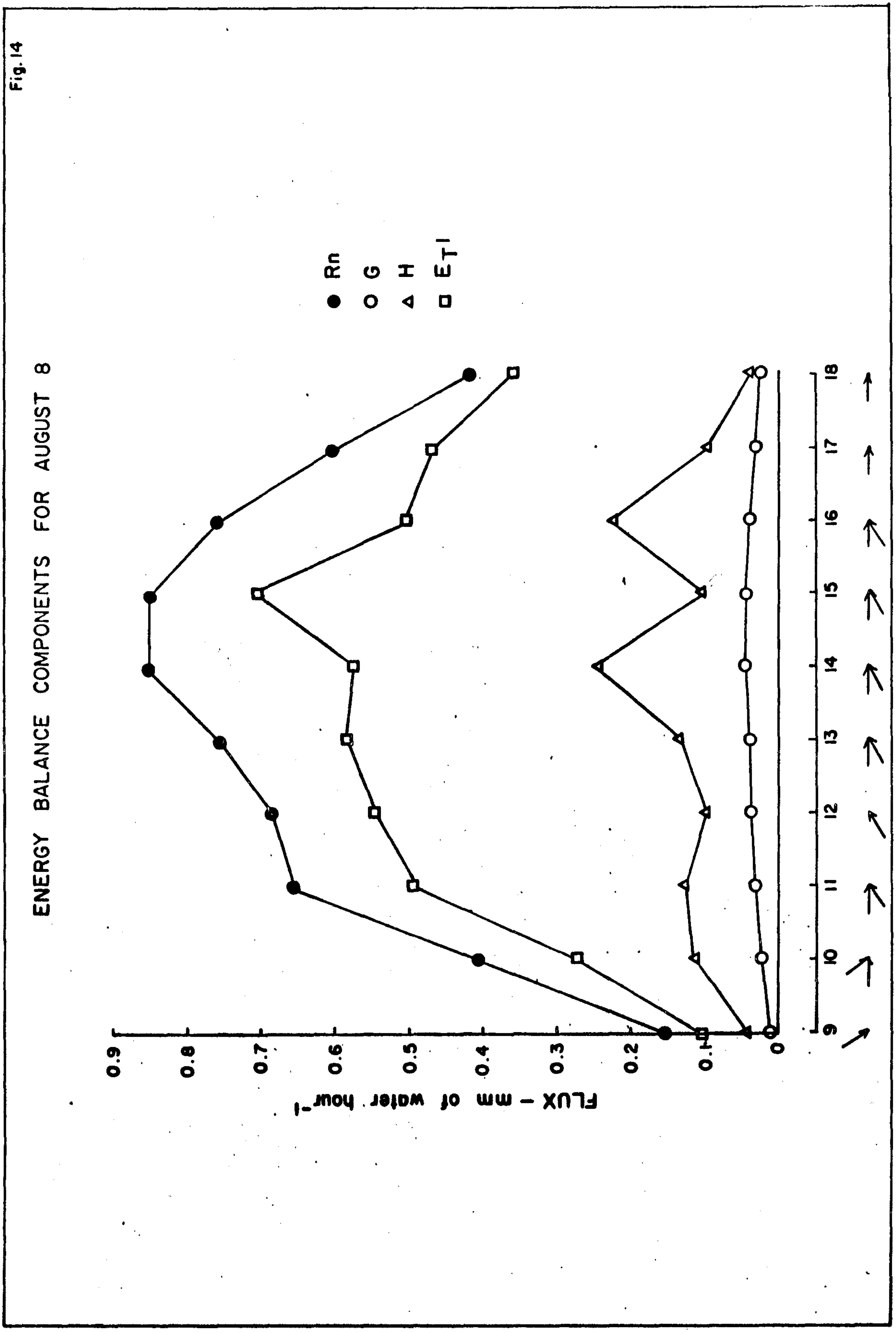


Fig. 14
ENERGY BALANCE COMPONENTS FOR AUGUST 8
Rn
G
H
E_T I
FLUX - mm of water hour^{-1}
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
9
10
11
12
13
14
15
16
17
18

had dried out markedly. The absolute amount of evapotranspiration was 3.5 mm compared to 4.6 mm on August 8. This again shows that water was becoming a limiting factor to evapotranspiration. An afternoon rise in sensible heat flux probably due to partial stomatal closure is again apparent under the daily maximum net radiation amount (Figure 15).

The important factors to note from this study of the four days' data are:

(1) the possible effect of the plant in limiting evapotranspiration probably through partial stomatal closure. This seems to have been operative in the afternoon, and the time seems to be dependent upon the intensity of radiation.

(2) the effect of progressive drying of the site on the energy fluxes. The marked decline in the ratio of $E_T1/\frac{Rn}{L}$ on August 11 occurred in spite of a rainfall total of 17.3 mm in the previous week (Figure 12). Since irrigation had been discontinued nine days previously, this amount of rainfall was clearly not enough to maintain evapotranspiration at the potential rate. This emphasizes the low moisture retention capacity of the soil and the importance of irrigation, in this situation, if it is considered desirable to have the crop transpiring at the potential rate.

2. <u>A Test of the Penman Model</u>

Evapotranspiration was evaluated using the Penman combination model (E_T2) for all days[4] and for individual hours on days when a complete energy

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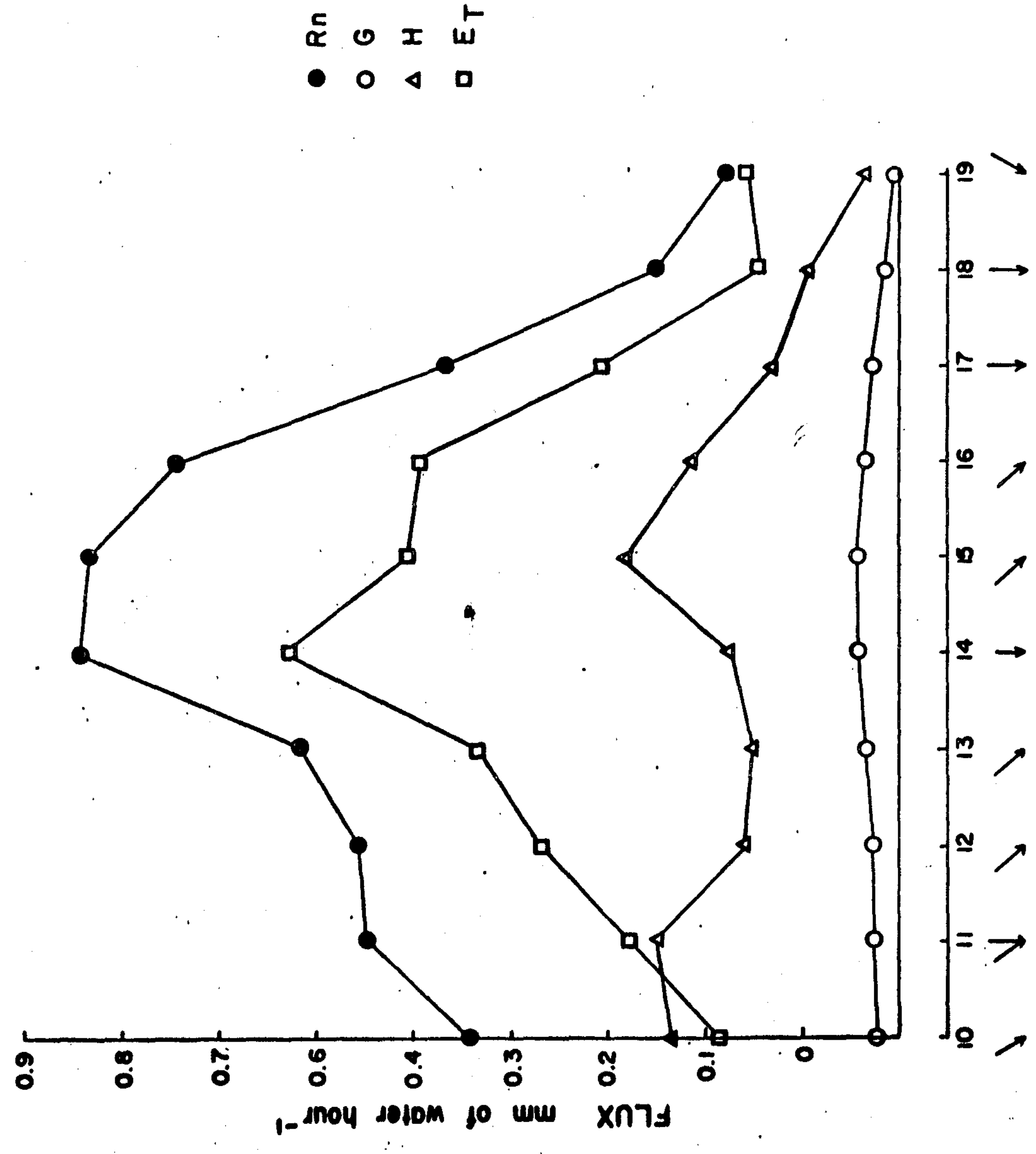
[4] Data for three days are missing because of instrumental problems.

Fig. 15

ENERGY BALANCE COMPONENTS FOR AUGUST 11



balance study was carried out. These results will be examined to show how the model performed both for daily[5] and hourly totals.

Determination of Z_o

In the evaluation of E_T2 values of Z_o were necessary. Z_o was obtained from wind profile measurements on thirteen days (Figure 16), and values for intervening days were found by linear interpolation. Z_o is calculated from the logarithmic wind profile during neutral conditions (Webb, 1965). Hence, on any one day, when the wind profile was measured, point readings of Z_o were chosen from the data, when the temperature profile was virtually neutral, and an average value was found.

Hourly Totals of Evapotranspiration

Hourly values of evapotranspiration are presented from the Bowen ratio method (E_T1), from the Penman model (E_T2), and from the water equivalent of the available energy (Rn-G) (E_T3) for all energy balance days when the measurements extended over more than six hours (Appendix B)[6]. Also, regression equations have been fitted to scatter diagrams of hourly values of measured evapotranspiration (E_T1) against calculated evapotranspiration (E_T2) for all days when the complete energy balance was evaluated (Appendix C)[6].

A comparison of all hourly values of E_T1 and E_T2 is shown in Figure 17. It is evident that the 1:1 line defines an upper limit to the scatter.

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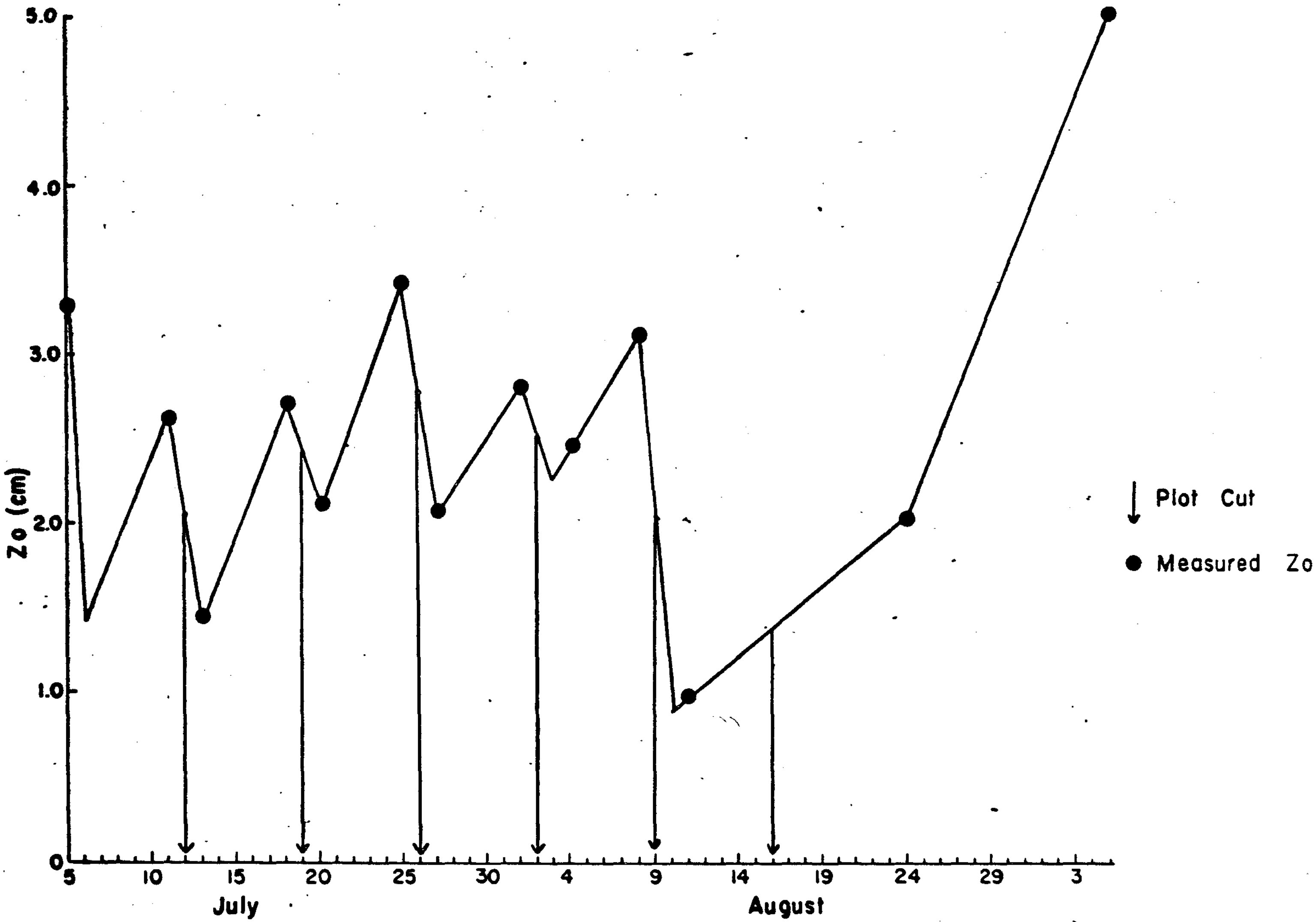
5 "Daily" refers to periods of positive net radiation.

6 The data for July 20 and August 17 are not included in Appendices.

Fig. 16

VARIATION OF Zo (average daily values) OVER THE EXPERIMENTAL PERIOD



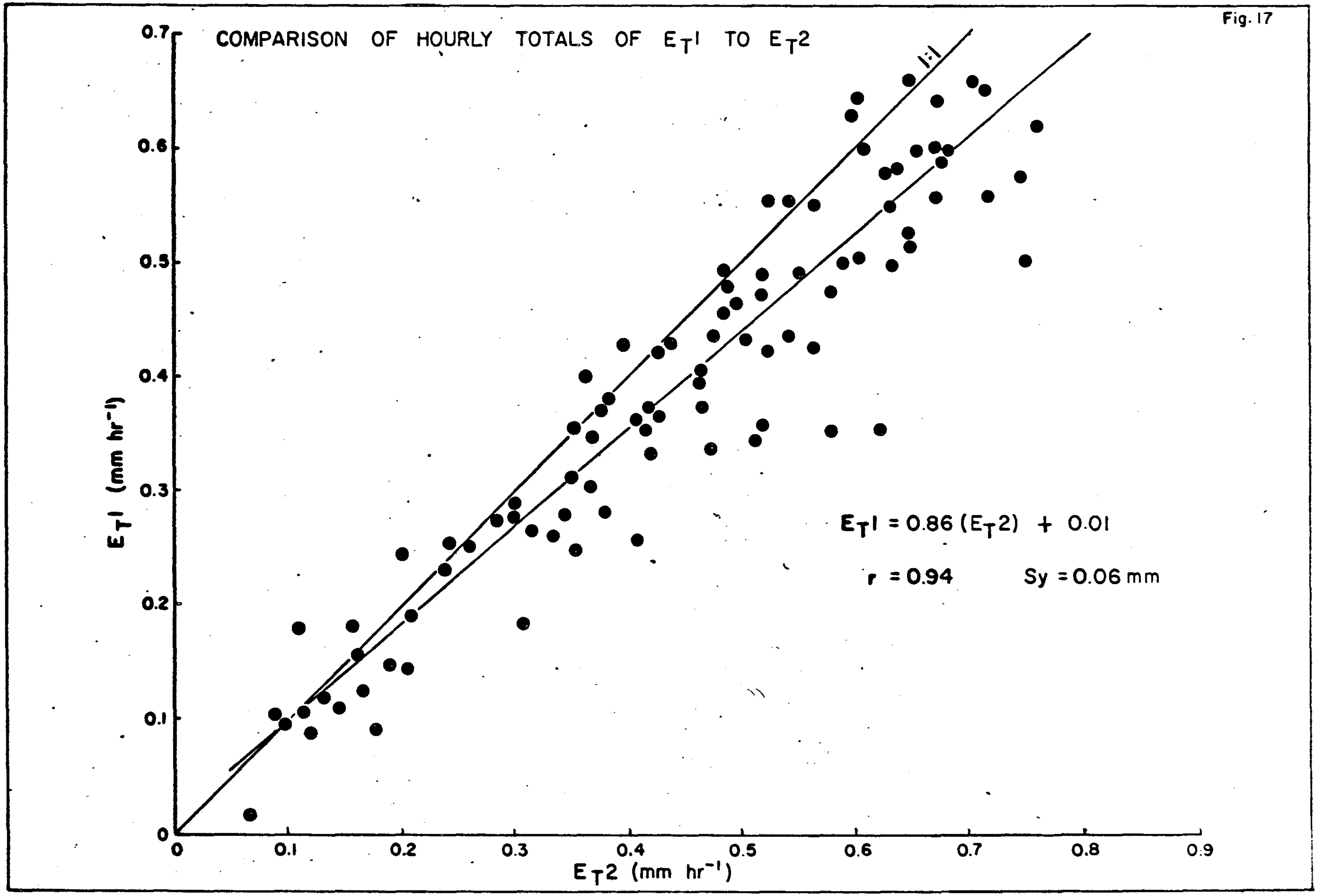


Fig. 17
COMPARISON OF HOURLY TOTALS OF E_T1 TO E_T2
1:1
$E_T1 = 0.86 (E_T2) + 0.01$
$r = 0.94$ Sy = 0.06 mm
E_T1 (mm hr^{-1})
E_T2 (mm hr^{-1})
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

If all points fell on the 1:1 line it would mean that the evapotranspiration was always at the potential rate. Since the scatter is predominantly below the 1:1 line, true potential evapotranspiration conditions were seldom operative. The regression intercept (a) and coefficient (b) describe how closely the evaporative flux approximated the potential rate. As $a \longrightarrow 0$ and $b \longrightarrow 1.0$ potential evapotranspiration conditions are approached.

The regression results from plots of E_T1 against E_T2 for each energy balance day are shown in Table 3.

Table 3

Regression parameters from E_T1 versus E_T2

Date	a	b
July 5 (morning)	0.08	0.54
July 5 (afternoon)	-0.02	1.0*
July 13	-0.02	1.01*
July 18	-0.06	0.95
July 20	0.03	0.97*
July 25	-0.02	0.80
July 27	-0.03	1.0*
August 4	0.01	0.84
August 8	0.08	0.71
August 11	-0.06	1.02
August 17	-0.01	0.86

* Potential evapotranspiration conditions operative.

Two days have been selected to show how the model performed under contrasting conditions: July 20 and August 17.

On July 20, the hourly values of E_T1 and E_T2 showed almost perfect agreement for the whole daylight period (Figure 18). The noticeable drop in E_T1 between 1200 and 1500 has already been attributed to partial stomatal closure. This feature of the curve was not detected by the Penman model since it uses temperature and vapour pressure values measured at 1.7 m. These are less sensitive to small changes in evapotranspiration at the surface than profiles values. Also, the measurements in the screen were taken on the hour, whereas gradient measurements for the hourly evaluation of E_T2 were time averages of six readings per hour. The scatter of E_T1 against E_T2 (Figure 19) yielded the equation,

$$E_T1 = 0.97\ (E_T2) + 0.03 \qquad (22)$$

The correlation coefficient (r) is 0.99, and the standard error (Sy) is 0.03 mm. Since the slope of the line is almost unity (0.97), and the intercept is small, the evapotranspiration can be considered potential on this day. Equation (22) shows that the model performed extremely well for hourly totals of evapotranspiration. This agrees with the work of van Bavel (1966), who showed that this type of model is adequate to estimate hourly totals of evapotranspiration over an irrigated, vegetated surface. When the hourly totals are summed for the day (ΣE_T), the agreement of measured and calculated evapotranspiration is within 3%.

In contrast to July 20, the graph for August 17 (Figure 18) shows poorer agreement. Fifteen days had elapsed since the last irrigation, and

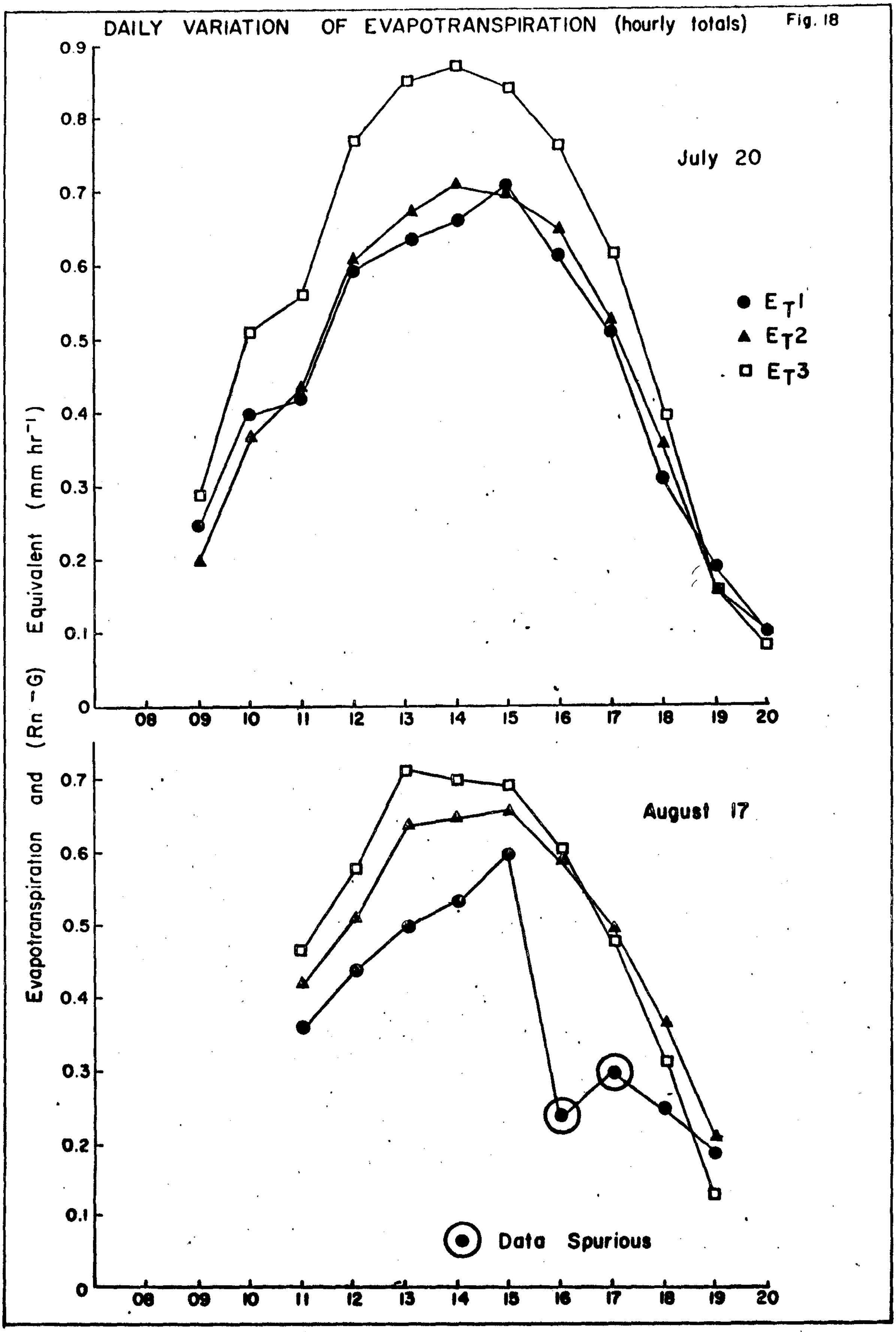
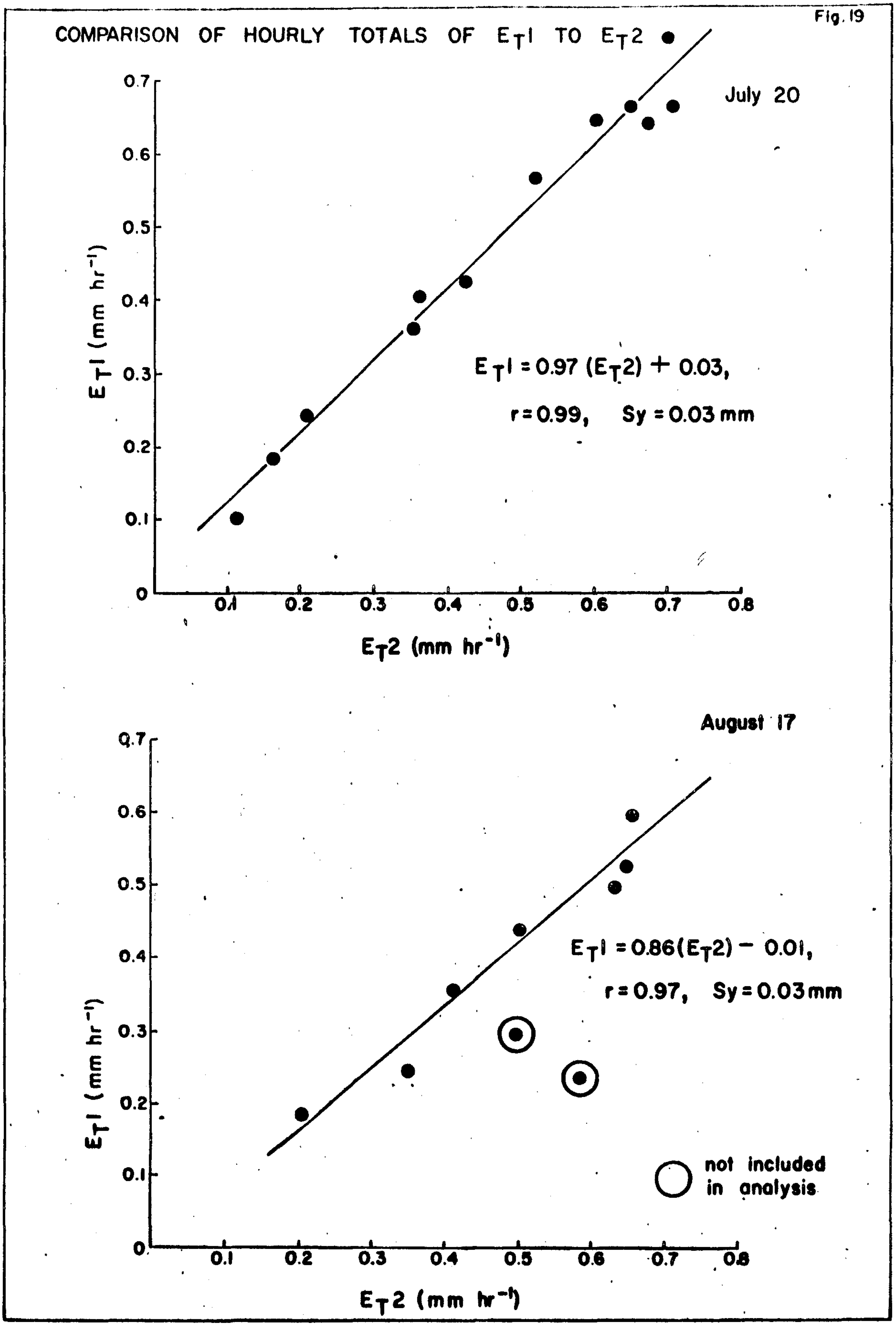

DAILY VARIATION OF EVAPOTRANSPIRATION (hourly totals)
Fig. 18
July 20
August 17
E_T1
E_T2
E_T3
Data Spurious
Evapotranspiration and (Rn − G) Equivalent (mm hr⁻¹)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
08
09
10
11
12
13
14
15
16
17
18
19
20

Fig. 19



COMPARISON OF HOURLY TOTALS OF E_T1 TO E_T2
July 20
E_T1 (mm hr⁻¹)
E_T2 (mm hr⁻¹)
E_T1 = 0.97 (E_T2) + 0.03,
r = 0.99, Sy = 0.03 mm
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
August 17
E_T1 = 0.86(E_T2) − 0.01,
r = 0.97, Sy = 0.03 mm
not included in analysis

there had been no rainfall in the previous week (Table 2). Under these conditions, water had become a limiting factor to evapotranspiration. The ratio $E_T1/\frac{Rn}{L}$ was 0.67, and clearly, evapotranspiration was not proceeding at the potential rate. The scatter for this day (Figure 19) yielded the equation,

$$E_T1 = 0.86\ (E_T2) - 0.01,$$
$$r = 0.97,\ Sy = 0.03mm \qquad (23)$$

Even though the correlation coefficient is high the disparity between E_T1 and E_T2 is shown by the slope of 0.86.

$\Sigma\ E_T2 > \Sigma\ E_T1$ by 21%. This lack of agreement is unacceptable and emphasizes that the model applies only to potential conditions and is not applicable for estimating evapotranspiration from areas where water is limiting.

The data for July 5 are of considerable interest. They show that cutting of the grass, to 4 cm, which occurred around noon, had a marked influence on the evaporative flux. The regression coefficient of E_T1 against E_T2 also changed markedly (Figure 20), illustrating that the evapotranspiration approached the potential rate. In terms of transpiration, cutting should produce the opposite effect since the leaf surface area and, therefore, evapotranspiration are reduced. Such a reduction was found by van Bavel (1966). It is probable that evapotranspiration increased following cutting because surface moisture, hitherto effectively shaded from the sun and sheltered from turbulent motion by the longer grass (25 cm), was exposed to the atmosphere.

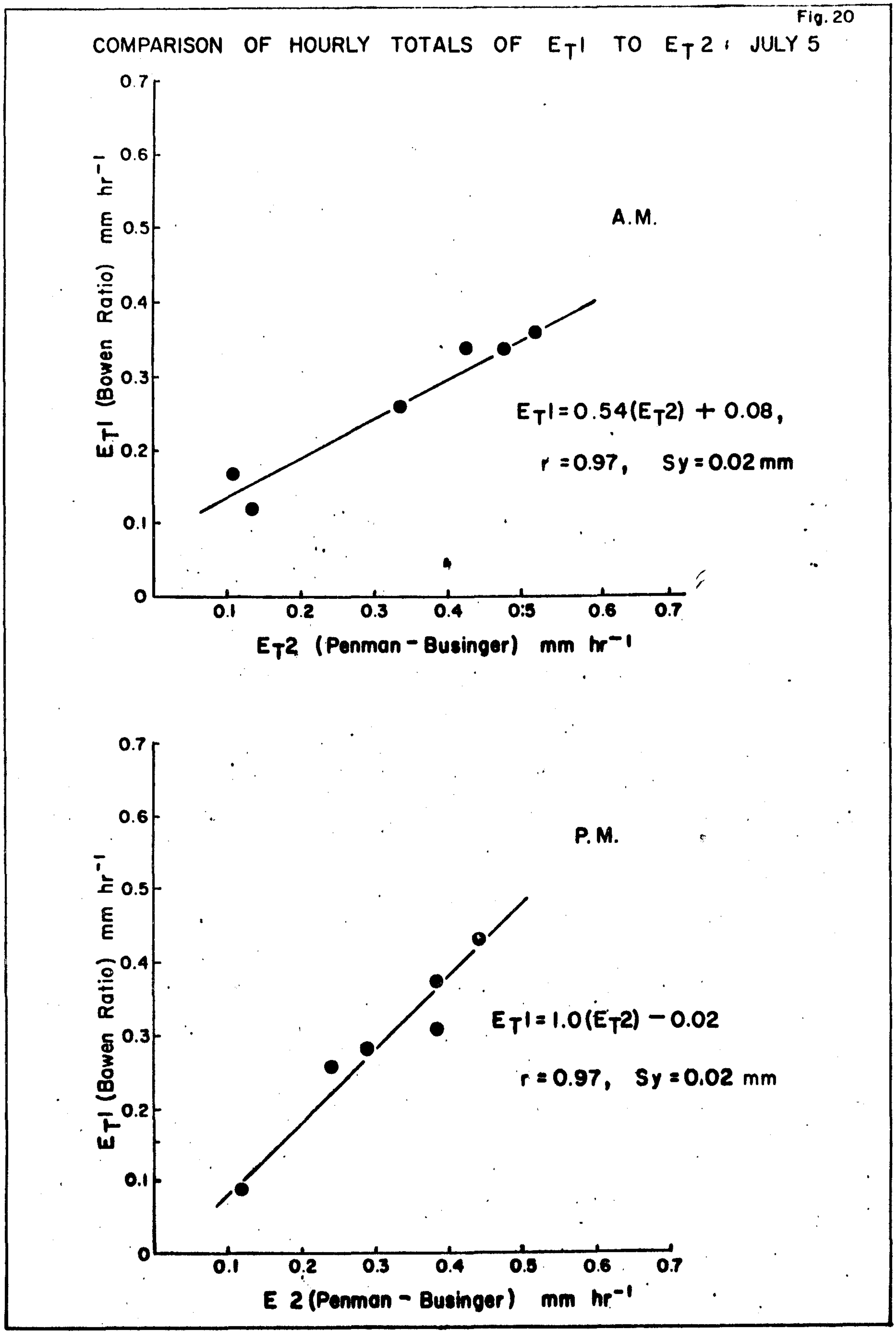


Fig. 20
COMPARISON OF HOURLY TOTALS OF E_T1 TO E_T2 : JULY 5
A.M.
$E_T1 = 0.54(E_T2) + 0.08$,
r = 0.97, Sy = 0.02 mm
E_T1 (Bowen Ratio) mm hr^{-1}
E_T2 (Penman - Businger) mm hr^{-1}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
P.M.
$E_T1 = 1.0(E_T2) - 0.02$
r = 0.97, Sy = 0.02 mm
E_T1 (Bowen Ratio) mm hr^{-1}
E 2 (Penman - Businger) mm hr^{-1}

One feature which is apparent from all days, except August 11, is that at some time during each day $E_T2 > E_T3$. It is particularly apparent on July 25 from 1600 to 2000 (Appendix B). Two explanations are possible. First, at screen level there was advection of warm, dry air, since the screen would be outside the boundary layer. This would give an anomalously large wet-bulb depression, and, therefore, an overestimate of evapotranspiration at the surface. Secondly, overheating could have occurred in the unventilated screen, and this can result in a dry-bulb temperature of as much as 1 C° greater than ambient air temperature (Handbook of Met. Instruments, 1956). The effect of overheating is the same as warm air advection in increasing the wet bulb depression. If screen heating were the main reason, it would have occurred most frequently in the afternoon, and, in fact, all the abnormal E_T2 values occur at this time. However, this is not conclusive evidence. The two reasons cannot be separated with the data available, and the phenomenon will be termed "apparent advection". To investigate it, temperature profiles were plotted between 15 cm and 170 cm for all hours when $E_T2 > E_T3$ (Appendix D). The temperature at 15 cm was treated as zero, and those at 45 cm and 170 cm as positive and negative deviations from zero. Out of the twenty profiles plotted, twelve showed "apparent advection". "Apparent Advectional" effects were most marked on July 25, when $E_T2 > E_T3$ for six hours out of eleven. The temperature profiles for this day are shown in Figure 21. Three of the profiles show the presence of apparent advection. These figures suggest that this is a reasonable hypothesis to

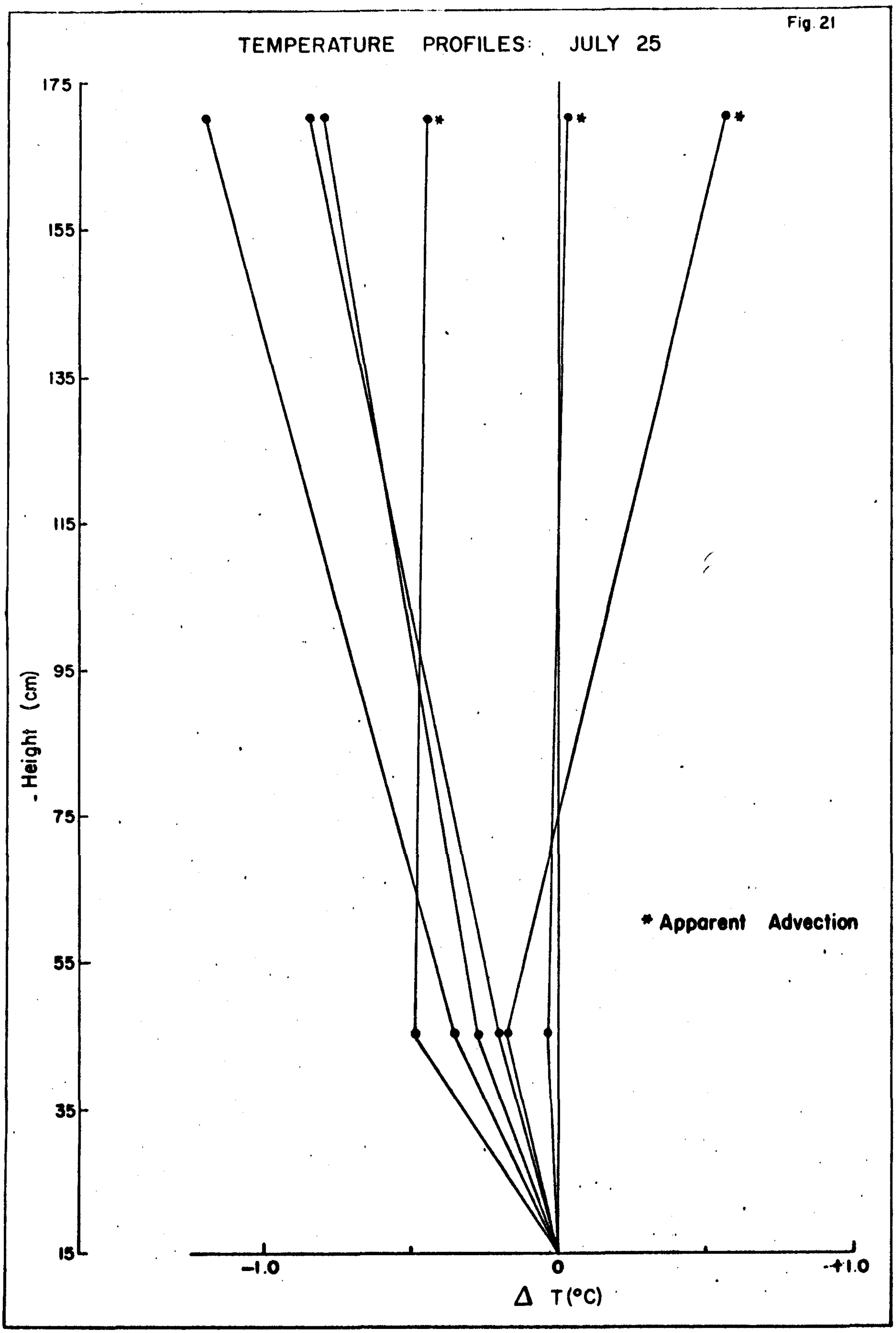


Fig. 21
TEMPERATURE PROFILES: JULY 25
175
155
135
115
95
75
55
35
15
Height (cm)
-1.0
0
+1.0
Δ T(°C)
* Apparent Advection

explain the twelve abnormal values of E_T2. No other hypothesis could be put forward to account for the remaining anomalies.

When evapotranspiration approached the potential rate (July 5 (afternoon), 13, 20 and 27), the model performed extremely well for hourly totals of evapotranspiration (within 10%). On July 13 and 20, the model values were within 5% of the measured (Table 4). In contrast to these days, when evapotranspiration was not at the potential rate the model values overestimated by as much as 31%.

Table 4

Comparison of hourly totals of E_T2 to E_T1

Date	E_T2/E_T1
July 5 (pre-cutting)	1.26
July 5 (post-cutting)	1.07
July 13	1.04
July 18	1.20
July 20	0.97
July 25	1.31
July 27	1.07
August 4	1.15
August 8	1.16
August 11	1.16
August 17	1.21

The scatter shown in Figure 17 of all hourly totals of evapotranspiration yielded the equation,

$$E_T1 = 0.86\ (E_T2) + 0.01, \qquad (24)$$

$$r = 0.94, \ Sy = 0.06 \text{ mm}$$

This equation is very satisfactory as it accommodates data from days when evapotranspiration was continuing at the potential rate and days when this was not the case. Using equation (24), average values of evapotranspiration could be predicted from model values.

The scatter of hourly totals of E_T1 versus E_T3 (Figure 22) is fitted by the equation,

$$E_T1 = 0.74\ (E_T3) + 0.02, \qquad (25)$$

$$r = 0.96, \ Sy = 0.05 \text{ mm}$$

In terms of the correlation coefficient equation (25) is more satisfactory than equation (24). However if E_T3 is used as the predictor of E_T1, it will result in a definate overestimation. The regression results from E_T1 versus E_T3 for each energy balance day are shown in Table 5.

On days when true potential evapotranspiration conditions were approached (July 13, 20 and 27), values of b ranged from 0.76 to 0.78. When all days are considered b ranged from 0.70 to 0.78, which shows that b is conservative over the range of soil moisture conditions encountered. Because of the conservative nature of b, E_T3 does not differentiate between days of different moisture availability as well as the Penman model. The results for August 4 are suspect because of the small sample (5 values).

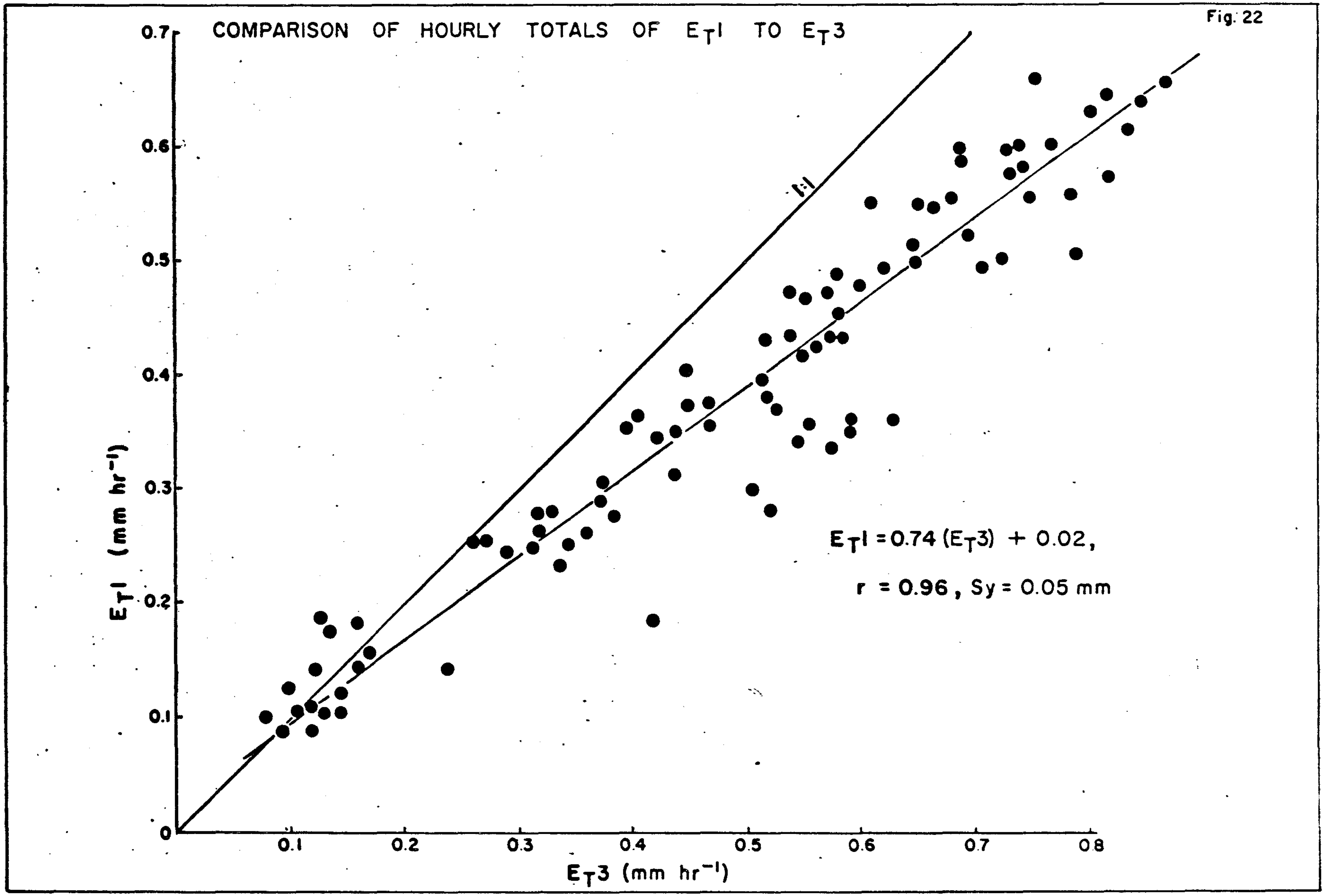


Fig. 22
COMPARISON OF HOURLY TOTALS OF E_T1 TO E_T3
1:1
$E_T1 = 0.74 (E_T3) + 0.02$,
$r = 0.96$, $Sy = 0.05$ mm
E_T1 (mm hr^{-1})
E_T3 (mm hr^{-1})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

The data for July 5 (morning) and August 17 present a special case which cannot be treated with the data available.

Table 5

Regression parameters from E_T1 versus E_T3

Date	a	b
July 5 (morning)	0.09	0.43
July 5 (afternoon)	0.03	0.75
July 13	0.01	0.78
July 18	0.01	0.78
July 20	0.04	0.76
July 25	0.04	0.70
July 27	0.02	0.77
August 4	0.15	0.56
August 8	0.03	0.73
August 11	-0.03	0.73
August 17	0.07	0.65

Daily totals of evapotranspiration

In the calculation of daily evapotranspiration using the Penman model, the temperatures and the vapour pressures were averages of three readings from the screen. These readings were normally taken at 0800, 1400 and 2000. To check the validity of this approach, daily totals of evapotranspiration using average temperatures and vapour pressures (E_T4) are compared with daily totals found by the summation of hourly totals. Since only half the days when hourly energy balance studies were carried out refer to periods of more than ten hours, the comparison is limited (Table 6). It can be seen that the computation of evapotranspiration using daily averages of temperature and vapour pressure gave essentially the same result (within 6%). A similar conclusion was reached by van Bavel (1966).

From these data it is clear that the Penman model works satisfactorily for both hourly and daily totals of evapotranspiration. However, the model is limited in application to periods when water is non-limiting. This is in agreement with the results of Tanner and Pelton (1960), in Wisconsin. Slatyer and McIlroy (1961) also reported that the Penman model performed satisfactorily for daily totals of evapotranspiration at Aspendale.

Monteith (1966) has shown that mean monthly values of evapotranspiration from an irrigated crop in S.E. England can be closely approximated by the water equivalent of net radiation. Tanner and Pelton (1960) found the water equivalent of net radiation closely approximated daily evapotranspiration when water was non-limiting.

Table 6

Comparison of E_T (daily totals) using summed hourly and mean data

Date (period-hours)	ΣE_T1 (mm)	ΣE_T2 (mm)	E_T4 (mm)	E_T1/E_T2	E_T1/E_T4
July 13 (10)	4.28	4.33	4.14	0.99	1.03
July 20 (12)	5.59	5.44	5.15	1.03	1.09
July 25 (11)	4.34	5.70	5.54	0.76	0.78
August 8 (9)	4.59	5.27	5.07	0.87	0.91
August 11 (10)	3.49	3.94	4.10	0.89	0.85
			Weighted average	0.93	0.93

They considered potential evapotranspiration to be operative when $E_T/\frac{Rn}{L} \geqslant .90$. In this study, when the daily totals of E_T2 and E_T3 were compared (Figure 23), the data yielded

$$E_T2 = 0.86\ (E_T3) - 0.18, \qquad r = 0.94,\ Sy = 0.40\ \text{mm} \tag{26}$$

This relation is very satisfactory. The y-intercept is close to 0, and thus, potential evapotranspiration is approximately 0.86 of $\frac{Rn - G}{L}$.

If the soil heat flux is not considered, this ratio will become 0.82. The figure of 0.82 is in agreement with a common finding (see section 1) that, when water loss from a crop is continuing at the potential rate, in the absence of advection, it is closely approximated by 0.8 to 0.9 of Rn. Because the scatter around the regression line is fairly small (r = 0.94), it is reasonable to assume that evapotranspiration from the ryegrass surface approached the potential rate for much of the season. The scatter of points above the upper limit of error indicates time when the surface was drying out, and, therefore, the model values became too high.

3. Potential Evapotranspiration and Productivity

To test the hypothesis that cumulative productivity of grass is linearly related to cumulative potential evapotranspiration (Penman, 1962), weekly[7] dry matter accumulation was calculated. The results are shown in Table 7. The data are compared (Figure 24) and fitted by a line drawn by eye. The linear relationship for most of the season is apparent.

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[7] The period between samples was eight days in one case, July 5 to July 13, and two weeks in another, August 22 to September 5.

Fig. 23

COMPARISON OF DAILY TOTALS OF E_T2 TO E_T3

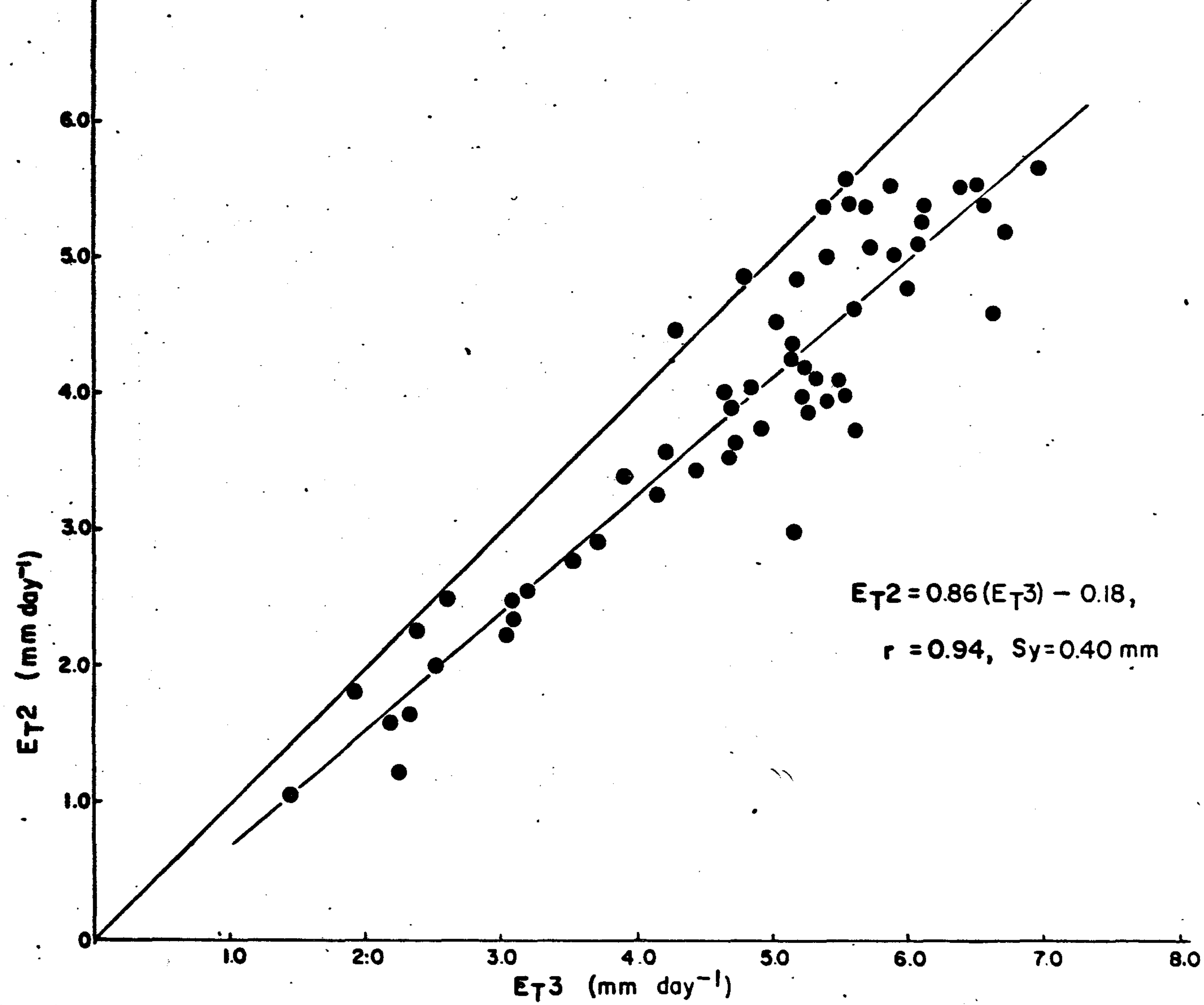


Table 7

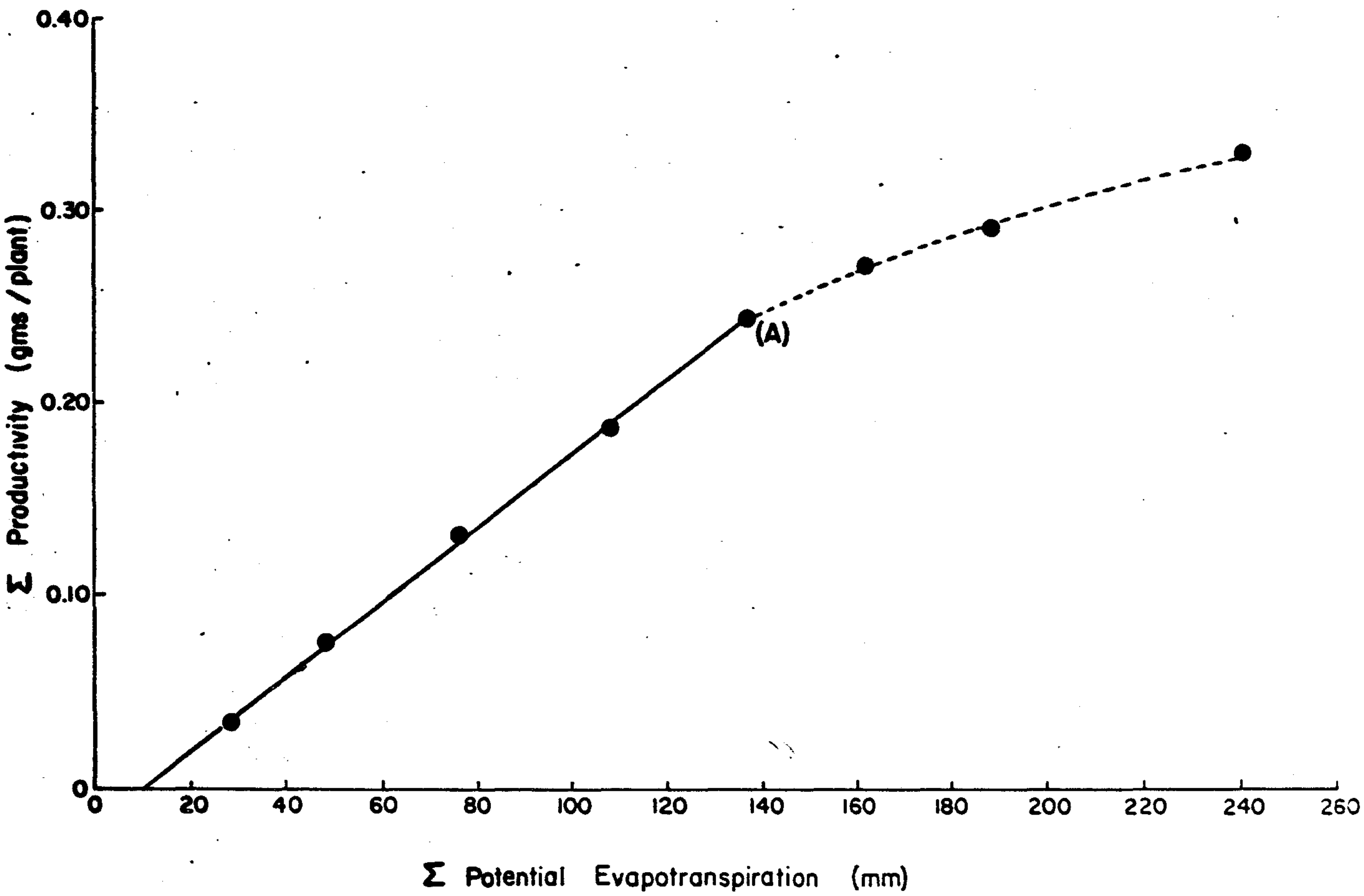
Cumulative productivity and cumulative PE data

Sampling date	Productivity (D.W.I.,[8] gms/plant)	Cumulative productivity (Σ D.W.I. gms/plant)	Cumulative PE (Σ PE mm)
July 5	0	0	0
July 13	0.032	0.032	26.6
July 19	0.043	0.075	48.2
July 25	0.060	0.130	76.2
August 1	0.055	0.185	107.2
August 8	0.057	0.242	137.0
August 15	0.028	0.270	162.2
August 22	0.020	0.290	188.3
September 5	0.039	0.329	241.0

[8] Dry weight increase, excluding roots.

Fig. 24

RELATIONSHIP BETWEEN Σ PRODUCTIVITY OF PERENNIAL RYEGRASS AND Σ PE



It is not potential evapotranspiration, per se, which is critical in this relationship (Monteith, 1966). The hypothesis holds because photosynthesis is governed by the income of solar radiation which is linearly related to net radiation. Since potential evapotranspiration is close to the water equivalent of net radiation, dry matter production, in an irrigated crop, transpiring at the potential rate and still in the vegetative stage, will be linearly related to the amount of water loss.

The hypothesis is substantiated up to August 8, (A). The simplest reason to explain the divergence from linearity therefore, is that evapotranspiration fell off as water became limiting, and, therefore, growth was reduced by stomatal closure which reduced CO_2 exchange between the plant and the atmosphere (Monteith 1966). This reasoning is justified because irrigation was discontinued from August 2 to August 23. During this period, the crop showed marked browning. Another possible reason is that the crop had reached the reproductive stage, and senescence was beginning (Leopold, 1961). This would mean that most of the energy synthesised as plant nutrients, would be going into the reproductive organs leading to a reduction in vegetative growth. There is no data to test this latter hypothesis but it seems reasonable since plot cutting was discontinued on August 16 and the crop would no longer be held at the vegetative phase (Penman, 1962).

A further point of interest from Figure 24 is that the line does not pass through the origin. A possible explanation lies in the fact that the grass was cut on July 5, and after cutting it took some time for new growth to appear, even though active transpiration was still continuing.

CONCLUSIONS

When the conditions of potential evapotranspiration are fulfilled the Penman combination model, using measured net radiation and an improved wind function, predicts both hourly and daily evaporative loss to within 5%. This level of prediction is obtained both for cloudless and cloudy-bright days. When water becomes limiting the model overestimates. In this experiment the maximum overestimation was 31% on a daily basis.

It is as valid to use mean daily data to calculate daily evapotranspiration as it is to use summed hourly totals. This is significant because it is unlikely that a period shorter than a day will be widely used. This is particularly true in irrigation prediction.

It has been shown that the plant has a limiting effect on the hourly evaporative flux probably through partial stomatal closure. This effect usually occurs in the early afternoon but the exact time seems to depend on radiation intensity.

The application of this model to spatial studies is to be recommended, particularly since it works both for cloudless and cloudy-bright conditions. All of the parameters except net radiation and Z_o are widely measured in climatological networks. The lack of measurement of net radiation could be overcome by utilizing established empirical relationships such as those based on solar radiation and cloudiness data. The parameter Z_o could be estimated from an established vegetation-height/Z_o relationship (Tanner and Pelton, 1960).

A continuing problem in evaporation prediction is the effect of soil moisture depletion on the evaporative flux. It has been shown that the Penman model is more sensitive to changes in the evaporative flux than the water equivalent of net radiation. Over the range of soil moisture encountered at Simcoe the latter was a relatively conservative quantity. It may be possible to predict actual evapotranspiration from a knowledge of net radiation and soil moisture change but special studies are needed.

It has further been shown that cumulative productivity of the crop is linearly related to cumulative potential water loss. This is a simple relationship which could be very beneficial in irrigation planning. However the relationship requires more rigorous testing, particularly for crops not kept at the vegetative phase of growth by regular cutting.

APPENDIX A

Energy Balance Data for Perennial Ryegrass

The following symbols are used:

ID = the time period (hour - day - month)

Rn = net radiation (mm water hr^{-1})

E_T1 = evapotranspiration from the Bowen ratio method (mm water hr^{-1})

E_T2 = evapotranspiration from the Penman model (mm water hr^{-1})

H = sensible heat flux to the air (mm water hr^{-1})

G = Soil heat flux (mm water hr^{-1})

ΔT_D = mean hourly dry-bulb temperature gradient (°C)

Δe = mean hourly vapour pressure gradient (mb)

β = mean hourly Bowen ratio (dimensionless).

Hours are listed on the 24-hour clock and represent the time ending the period of measurement e.g. ID 160507 represents measurements between 1500 and 1600 on July 5.

The flux of any parameter is considered positive if directed towards the surface. In the following data there is no sign designation unless the direction of the flux is reversed from its normal direction. The normal direction of Rn flux is positive and for E_T, H and G it is negative, during daylight.

ID	Rn	E_T1	E_T2	H	G	ΔT_D	Δe	β
080507	0.141	0.174	0.108	+0.026	+0.007	-0.069	0.198	-0.230
090507	0.150	0.118	0.131	0.024	0.008	0.052	0.168	0.203
100507	0.610	0.333	0.424	0.247	0.030	0.431	0.390	0.728
110507	0.666	0.358	0.519	0.275	0.033	0.827	0.711	0.766
120507	0.577	0.338	0.474	0.210	0.029	0.758	0.807	0.619
130507	0.377	0.259	0.333	0.099	0.019	0.396	0.685	0.381
140507	0.390	0.304	0.368	0.067	0.019	0.345	1.042	0.218
150507	0.347	0.279	0.295	0.051	0.017	0.345	1.263	0.180
160507	0.491	0.372	0.380	0.093	0.026	0.500	1.293	0.255
170507	0.569	0.428	0.438	0.113	0.028	0.758	1.904	0.262
180507	0.284	0.252	0.240	0.018	0.014	0.241	2.345	0.068
190507	0.095	0.084	0.118	0.016	+0.005	0.086	0.775	0.073
081307	0.134	0.103	0.088	0.024	0.007	0.121	0.338	0.235
091307	0.355	0.230	0.236	0.107	0.018	0.586	0.832	0.464
101307	0.547	0.382	0.385	0.138	0.027	0.655	1.205	0.358
111307	0.718	0.554	0.542	0.128	0.036	0.827	2.377	0.229
121307	0.730	0.309	0.538	0.384	0.037	1.178	0.619	1.255
131307	0.776	0.597	0.607	0.140	0.039	0.293	0.803	0.240
141307	0.629	0.479	0.487	0.119	0.031	0.689	1.792	0.253
151307	0.738	0.872	0.567	+0.097	0.037	-0.482	1.650	-0.193
161307	0.335	0.276	0.299	0.042	0.017	0.241	1.005	0.158
171307	0.337	0.261	0.315	0.059	0.017	0.207	0.608	0.224
181307	0.123	0.108	0.141	0.009	0.006	0.052	0.418	0.081
191307	0.113	0.106	0.112	0.001	0.006	0.013	0.673	0.013

ID	Rn	E_T1	E_T2	H	G	ΔT_D	Δe	β
121807	0.804	0.600	0.672	0.164	0.040	0.568	1.357	0.276
131807	0.875	0.617	0.757	0.214	0.044	0.724	1.351	0.353
141807	0.823	0.557	0.717	0.225	0.041	0.655	1.056	0.408
151807	0.852	0.742	0.758	0.067	0.043	0.293	1.918	0.101
161807	0.696	0.546	0.628	0.115	0.035	0.586	1.740	0.222
171807	0.585	0.425	0.562	0.131	0.029	0.534	1.104	0.319
181807	0.422	0.366	0.425	0.035	0.021	0.241	1.507	0.105
191807	0.122	0.088	0.175	0.028	0.006	0.439	0.905	0.320
201807	0.013	0.014	0.066	+0.002	+0.001	-0.103	0.566	-0.120
092007	0.304	0.244	0.198	0.045	0.015	0.241	0.872	0.182
102007	0.527	0.399	0.364	0.102	0.026	0.706	1.780	0.261
112007	0.586	0.418	0.425	0.139	0.029	0.913	1.791	0.336
122007	0.801	0.641	0.600	0.120	0.040	0.999	3.431	0.192
132007	0.886	0.638	0.672	0.204	0.004	1.103	2.241	0.324
142007	0.906	0.656	0.703	0.205	0.045	1.154	2.355	0.323
152007	0.876	0.751	0.697	0.077	0.044	0.586	3.258	0.118
162007	0.788	0.658	0.645	0.091	0.039	0.534	2.380	0.148
172007	0.641	0.551	0.524	0.058	0.032	0.362	2.092	0.114
182007	0.413	0.355	0.353	0.037	0.021	0.293	1.668	0.116
192007	0.165	0.183	0.159	+0.010	+0.008	-0.379	1.744	-0.143
202007	0.078	0.096	0.099	+0.014	+0.004	-0.448	1.339	-0.220

ID	Rn	E_T1	E_T2	H	G	ΔT_D	Δe	β
102507	0.460	0.346	0.366	0.091	0.023	0.345	0.845	0.267
112507	0.682	0.499	0.587	0.149	0.034	0.534	1.165	0.302
122507	0.771	0.598	0.678	0.134	0.039	0.448	1.294	0.228
132507	0.723	0.586	0.675	0.101	0.036	0.517	1.922	0.177
142507	0.680	0.514	0.646	0.132	0.034	0.362	0.909	0.262
152507	0.472	0.374	0.463	0.074	0.024	0.172	0.552	0.206
162507	0.583	0.354	0.580	0.200	0.029	0.482	0.557	0.570
172507	0.621	0.351	0.622	0.239	0.031	0.362	0.347	0.688
182507	0.443	0.343	0.511	0.078	0.022	0.276	0.792	0.229
192507	0.280	0.252	0.408	0.014	0.014	0.034	0.374	0.061
202507	0.100	0.121	0.165	+0.026	0.005	-0.155	0.489	-0.209
102707	0.541	0.426	0.395	0.088	0.027	0.241	0.756	0.210
112707	0.611	0.454	0.484	0.126	0.031	0.500	1.160	0.284
122707	0.536	0.395	0.463	0.114	0.027	0.276	0.609	0.298
132707	0.609	0.487	0.519	0.092	0.030	0.327	1.114	0.194
142707	0.579	0.464	0.494	0.086	0.029	0.345	1.206	0.188
152707	0.163	0.144	0.188	0.011	0.008	0.052	0.418	0.081
120408	0.771	0.577	0.629	0.155	0.039	0.394	0.949	0.274
130408	0.787	0.554	0.670	0.194	0.039	0.411	0.766	0.354
140408	0.564	0.472	0.516	0.064	0.028	0.206	0.966	0.140
150408	0.469	0.403	0.463	0.043	0.023	0.120	0.726	0.109
160408	0.581	0.420	0.524	0.132	0.029	0.257	0.529	0.320

ID	Rn	E_T1	E_T2	H	G	ΔT_D	Δe	β
090808	0.152	0.101	0.110	0.043	0.008	0.240	0.375	0.442
100808	0.403	0.270	0.286	0.113	0.020	0.514	0.804	0.421
110808	0.654	0.492	0.483	0.129	0.033	0.668	1.647	0.267
120808	0.682	0.549	0.562	0.099	0.034	0.240	0.857	0.184
130808	0.751	0.581	0.638	0.132	0.038	0.531	1.495	0.234
140808	0.856	0.571	0.745	0.242	0.043	0.583	0.893	0.430
150808	0.848	0.704	0.759	0.102	0.042	0.343	1.472	0.153
160808	0.759	0.500	0.748	0.221	0.038	0.445	0.646	0.454
170808	0.598	0.470	0.529	0.098	0.030	0.274	0.825	0.219
180808	0.411	0.356	0.410	0.034	0.021	0.103	0.640	0.106
101108	0.440	0.181	0.307	0.237	0.022	0.600	0.302	1.308
111108	0.548	0.276	0.379	0.245	0.027	0.788	0.595	0.872
121108	0.554	0.369	0.420	0.157	0.028	0.651	1.008	0.426
131108	0.615	0.433	0.475	0.151	0.031	0.754	1.424	0.349
141108	0.846	0.629	0.596	0.175	0.042	0.668	1.584	0.278
151108	0.833	0.504	0.602	0.287	0.042	0.822	0.954	0.568
161108	0.742	0.491	0.550	0.214	0.037	0.874	1.322	0.435
171108	0.461	0.308	0.350	0.130	0.023	0.600	0.941	0.420
181108	0.247	0.143	0.204	0.092	0.012	0.445	0.458	0.641
191108	0.176	0.153	0.157	0.032	0.009	0.034	0.253	0.089
111708	0.489	0.352	0.413	0.113	0.024	0.314	0.629	0.329
121708	0.603	0.431	0.504	0.152	0.030	0.401	0.774	0.341

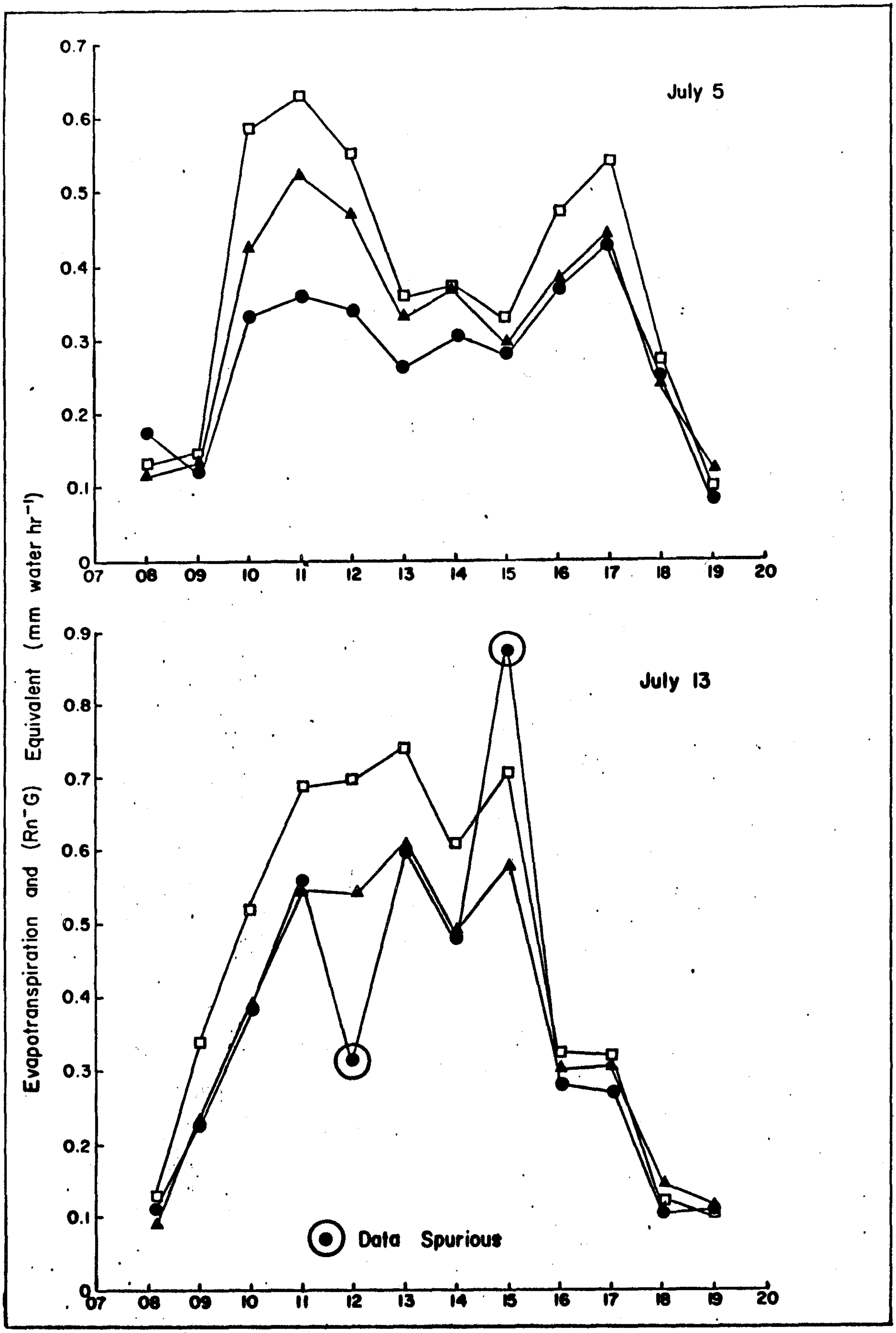
ID	Rn	E_T1	E_T2	H	G	ΔT_D	Δe	β
131708	0.741	0.494	0.633	0.210	0.037	0.767	1.151	0.439
141708	0.729	0.524	0.646	0.169	0.036	0.767	1.514	0.334
151708	0.720	0.595	0.655	0.089	0.036	0.383	1.586	0.159
161708	0.627	0.234	0.588	0.362	0.031	0.383	0.161	1.567
171708	0.492	0.293	0.494	0.174	0.025	0.293	0.317	0.609
181708	0.324	0.242	0.352	0.066	0.016	0.087	0.201	0.286
191708	0.132	0.187	0.209	+0.048	+0.007	-0.105	0.211	-0.326

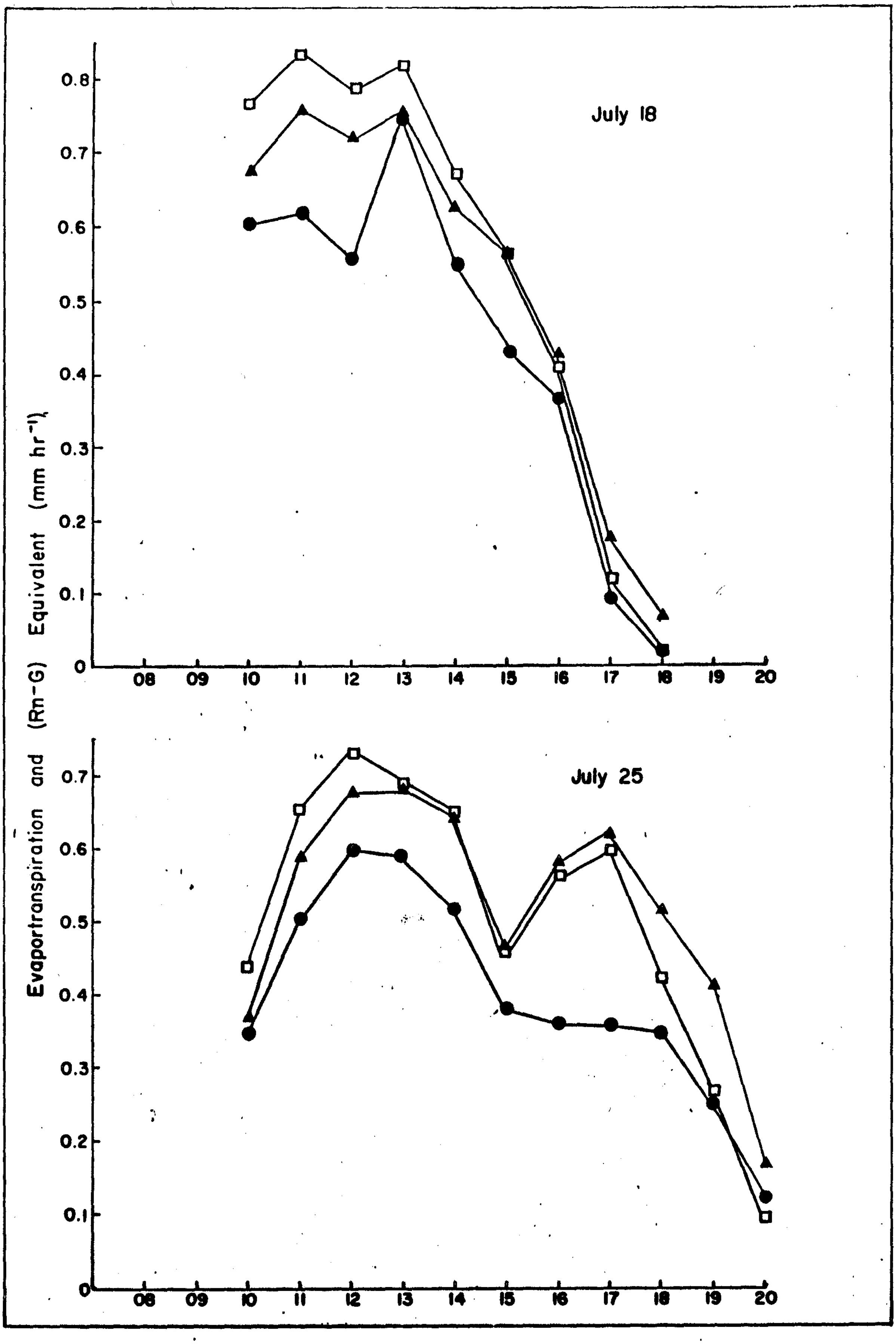
APPENDIX B

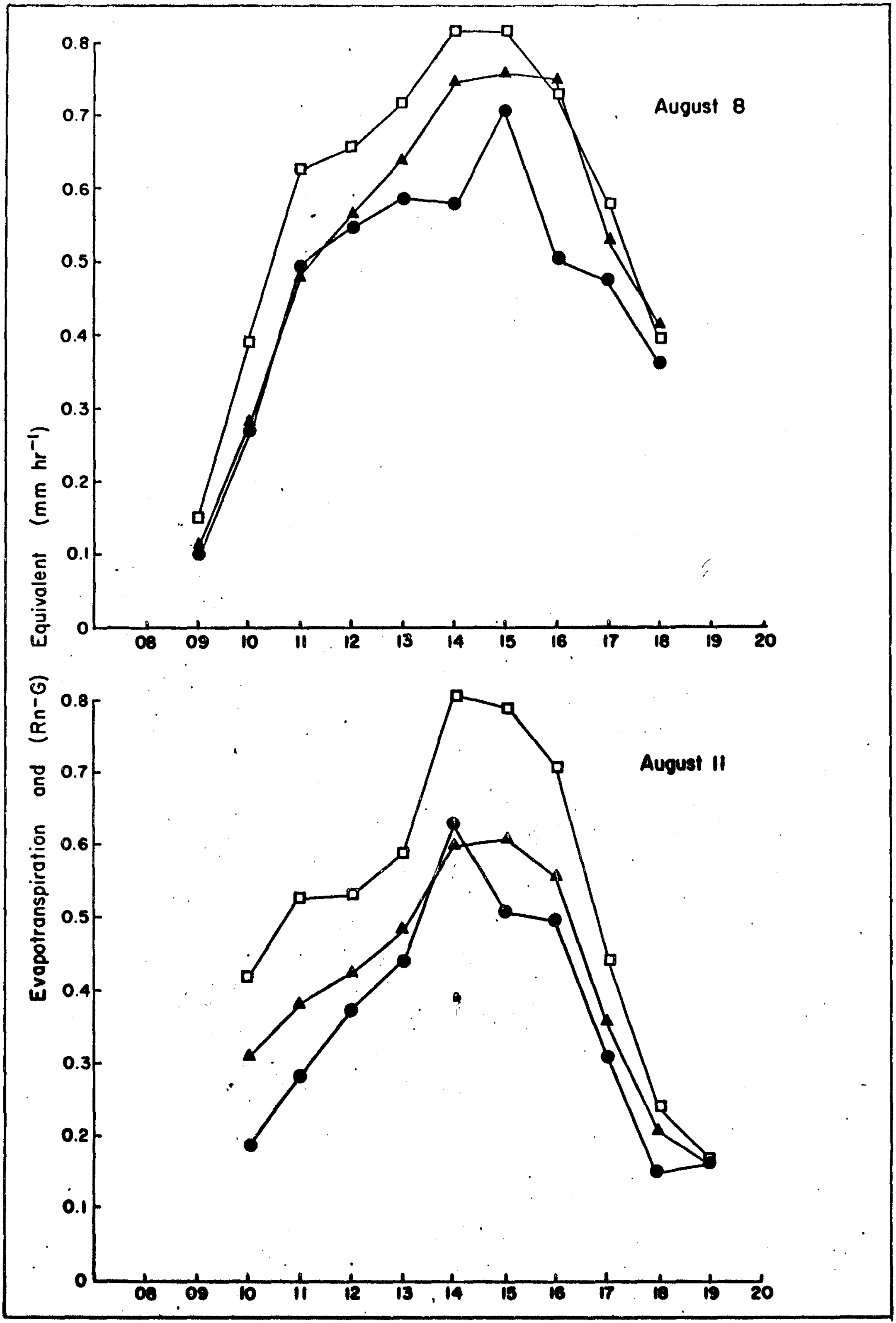
Daily variation of evapotranspiration

Symbols

●	E_T1
▲	E_T2
▣	E_T3


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
July 5
07
08
09
10
11
12
13
14
15
16
17
18
19
20
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
July 13
Data Spurious
Evapotranspiration and (Rn-G) Equivalent (mm water hr^{-1})

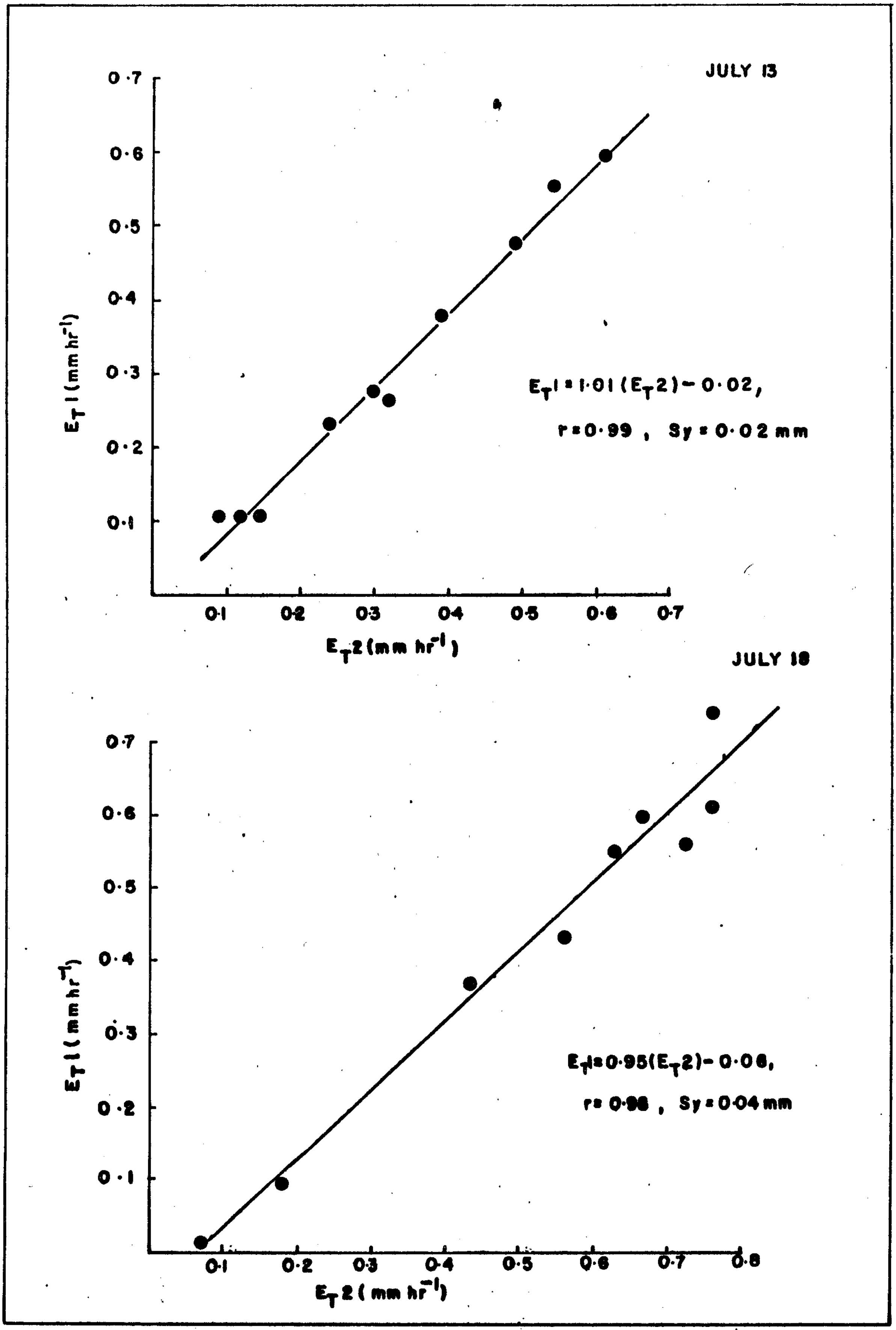

July 18
July 25
Evaporotranspiration and (Rn-G) Equivalent (mm hr⁻¹)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
08
09
10
11
12
13
14
15
16
17
18
19
20

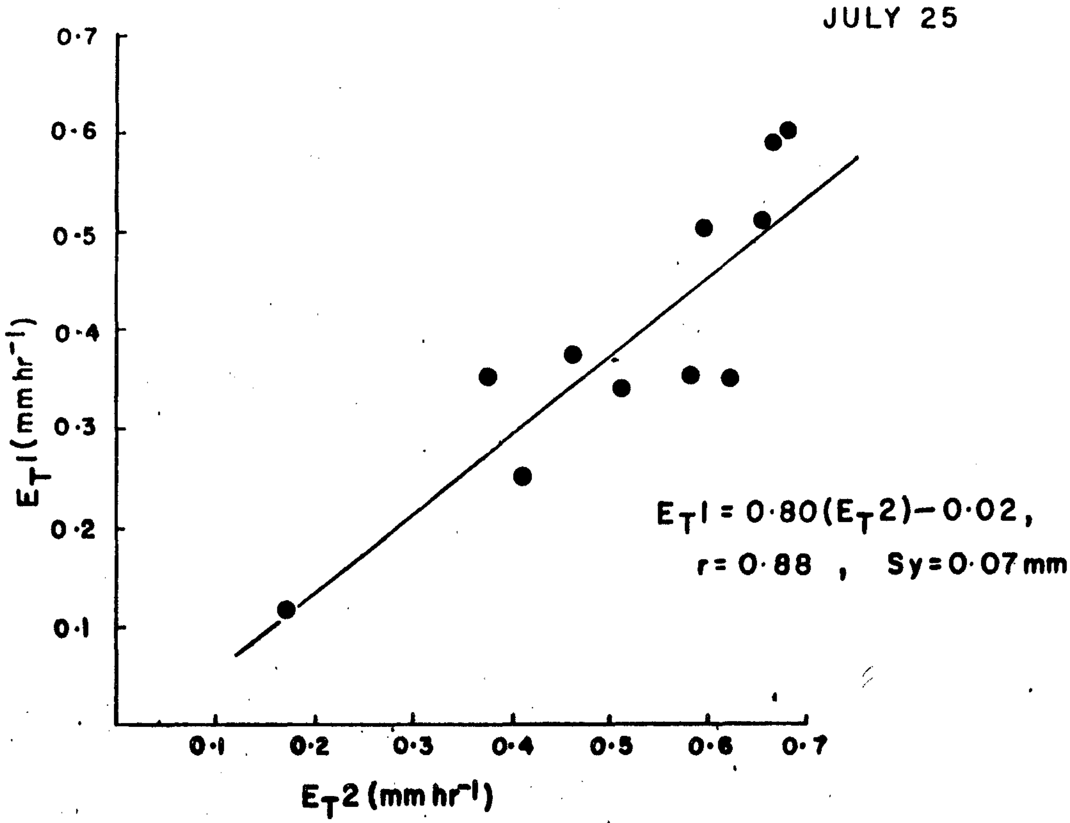


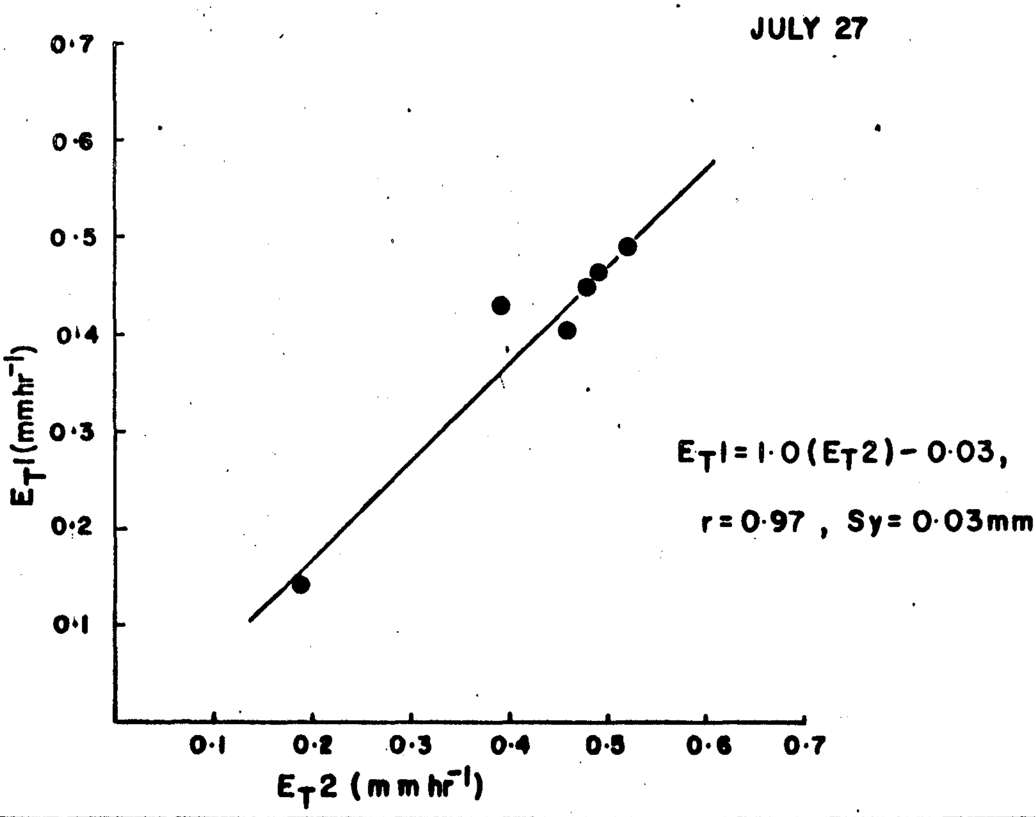
Evapotranspiration and (Rn-G) Equivalent (mm hr^{-1})
August 8
August 11
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
08 09 10 11 12 13 14 15 16 17 18 19 20

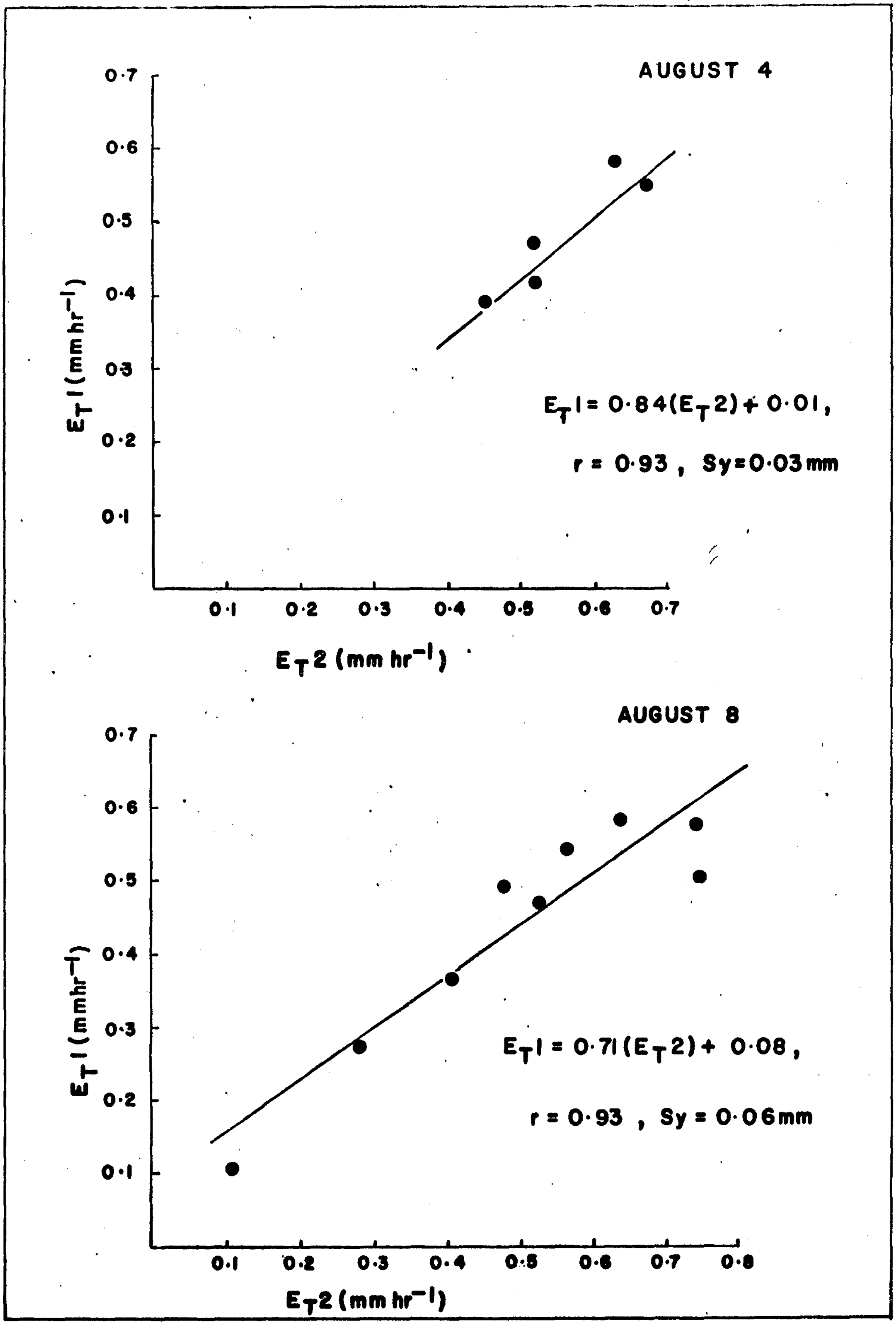
APPENDIX C

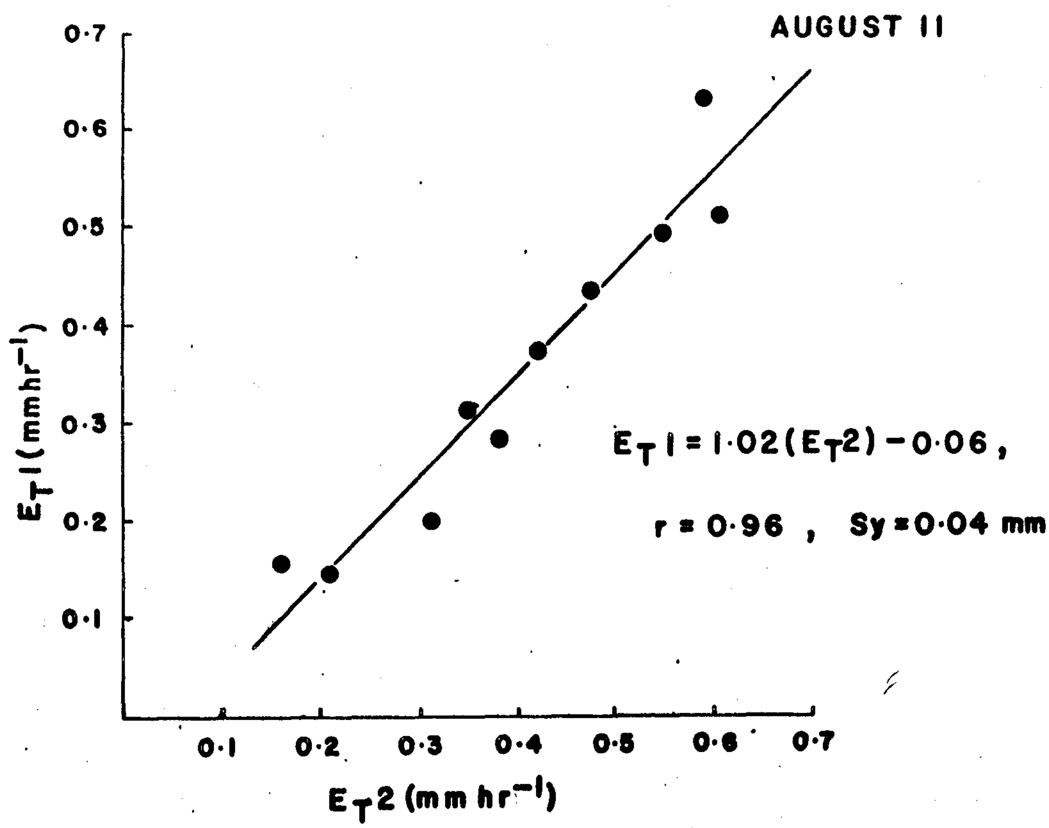
Daily comparison of E_T1 to E_T2


JULY 13
0·1
0·2
0·3
0·4
0·5
0·6
0·7
E_T1 (mm hr^{-1})
E_T2 (mm hr^{-1})
$E_T1 = 1·01 (E_T2) - 0·02,$
$r = 0·99$, $Sy = 0·02$ mm
JULY 18
0·8
E_T1 (mm hr^{-1})
E_T2 (mm hr^{-1})
$E_T1 = 0·95 (E_T2) - 0·06,$
$Sy = 0·04$ mm


JULY 25
0·7
0·6
0·5
0·4
0·3
0·2
0·1
E_T1 (mm hr^{-1})
0·1
0·2
0·3
0·4
0·5
0·6
0·7
E_T2 (mm hr^{-1})
$E_T1 = 0{\cdot}80(E_T2) - 0{\cdot}02,$
$r = 0{\cdot}88$, $Sy = 0{\cdot}07$ mm


JULY 27
0·7
0·6
0·5
0·4
0·3
0·2
0·1
E_T1 (mm hr^{-1})
0·1
0·2
0·3
0·4
0·5
0·6
0·7
E_T2 (mm hr^{-1})
$E_T1 = 1{\cdot}0(E_T2) - 0{\cdot}03,$
$r = 0{\cdot}97$, $Sy = 0{\cdot}03$ mm

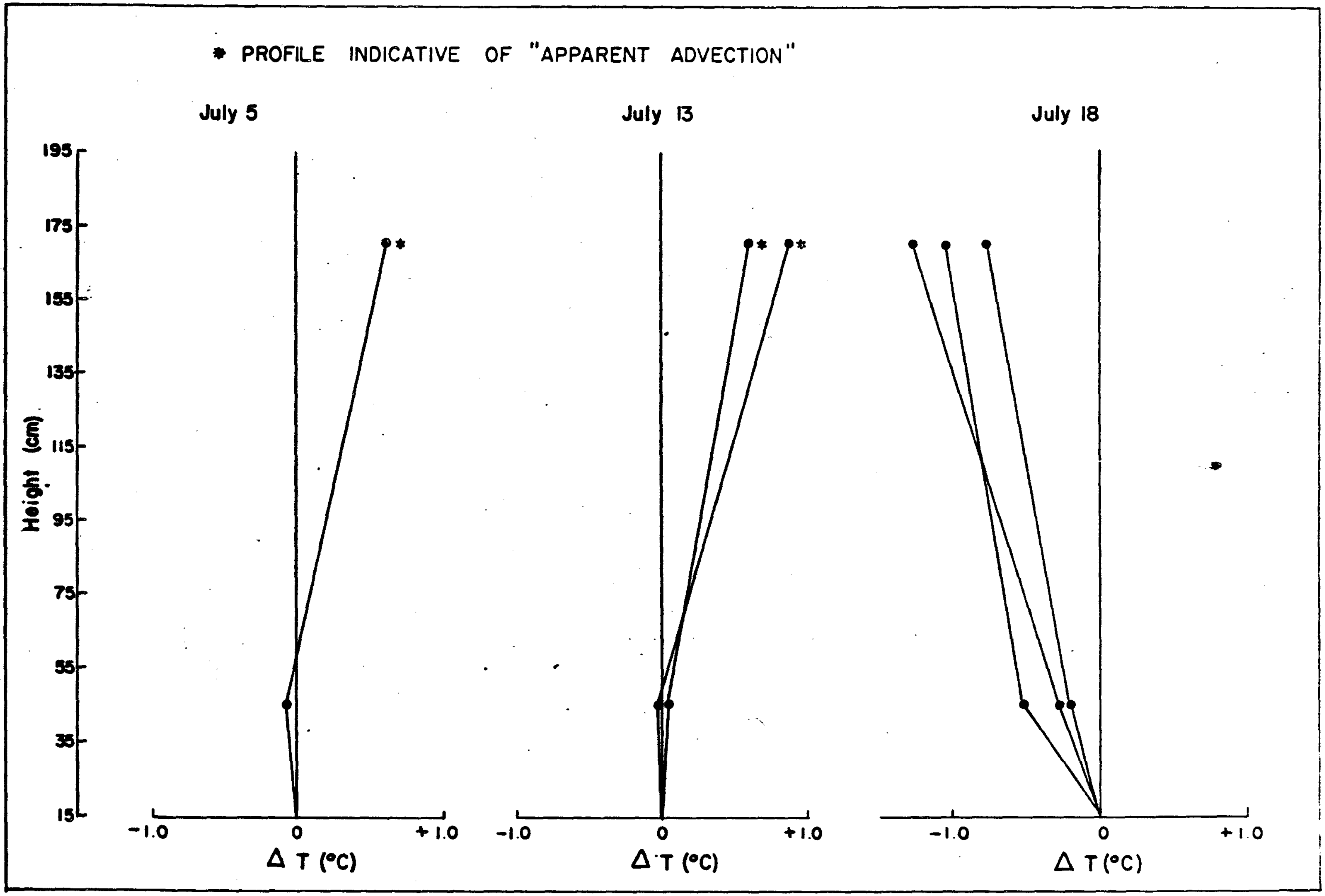

AUGUST 4
0·7
0·6
0·5
0·4
0·3
0·2
0·1
ET1 (mmhr⁻¹)
0·1 0·2 0·3 0·4 0·5 0·6 0·7
ET2 (mm hr⁻¹)
ET1 = 0·84(ET2) + 0·01,
r = 0·93 , Sy=0·03mm
AUGUST 8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
ET1 (mmhr⁻¹)
0·1 0·2 0·3 0·4 0·5 0·6 0·7 0·8
ET2 (mm hr⁻¹)
ET1 = 0·71(ET2) + 0·08,
r = 0·93 , Sy = 0·06mm

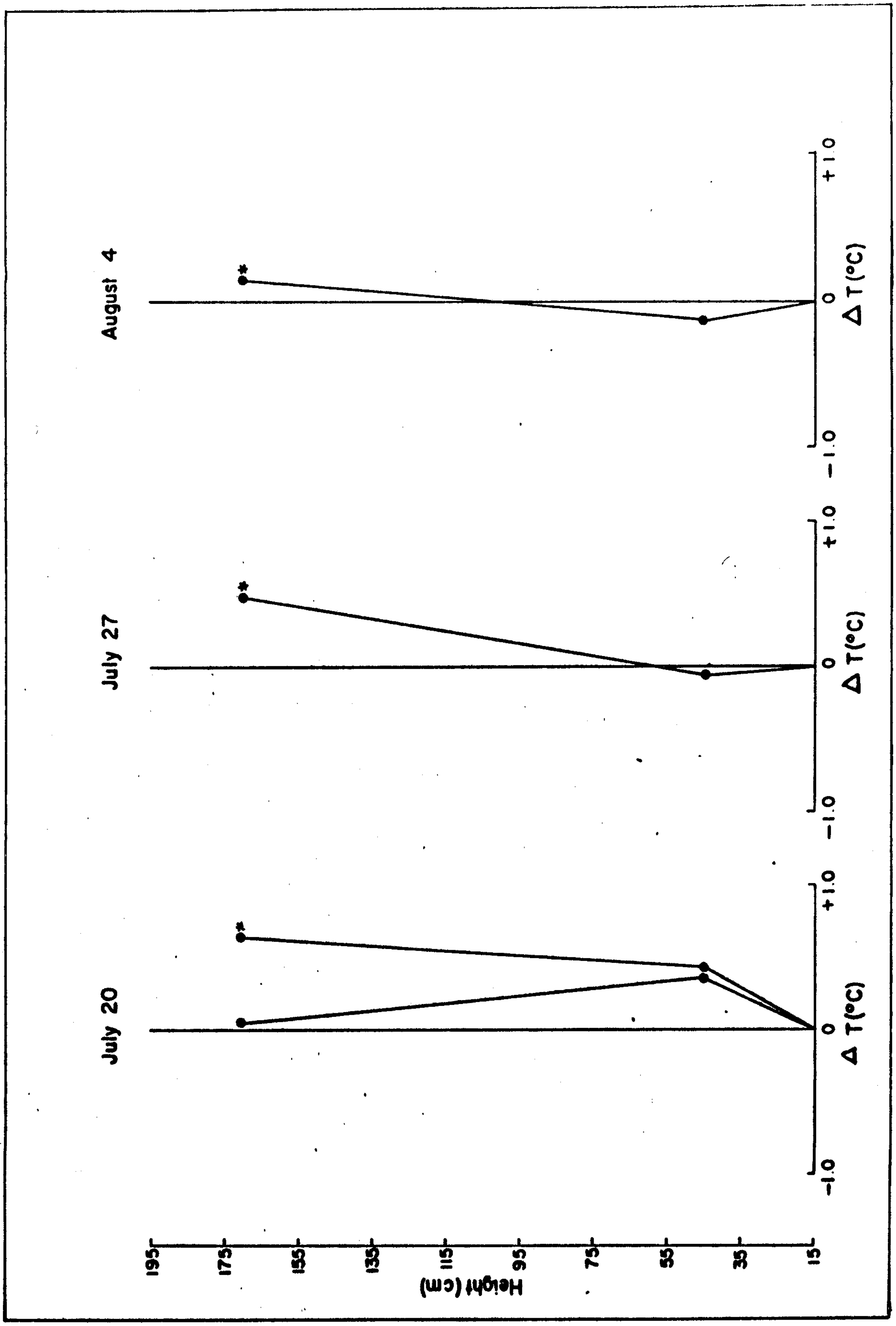


AUGUST 11
$E_T1 = 1.02(E_T2) - 0.06$,
$r = 0.96$, $Sy = 0.04$ mm
E_T1 (mmhr^{-1})
E_T2 (mm hr^{-1})
0·1
0·2
0·3
0·4
0·5
0·6
0·7

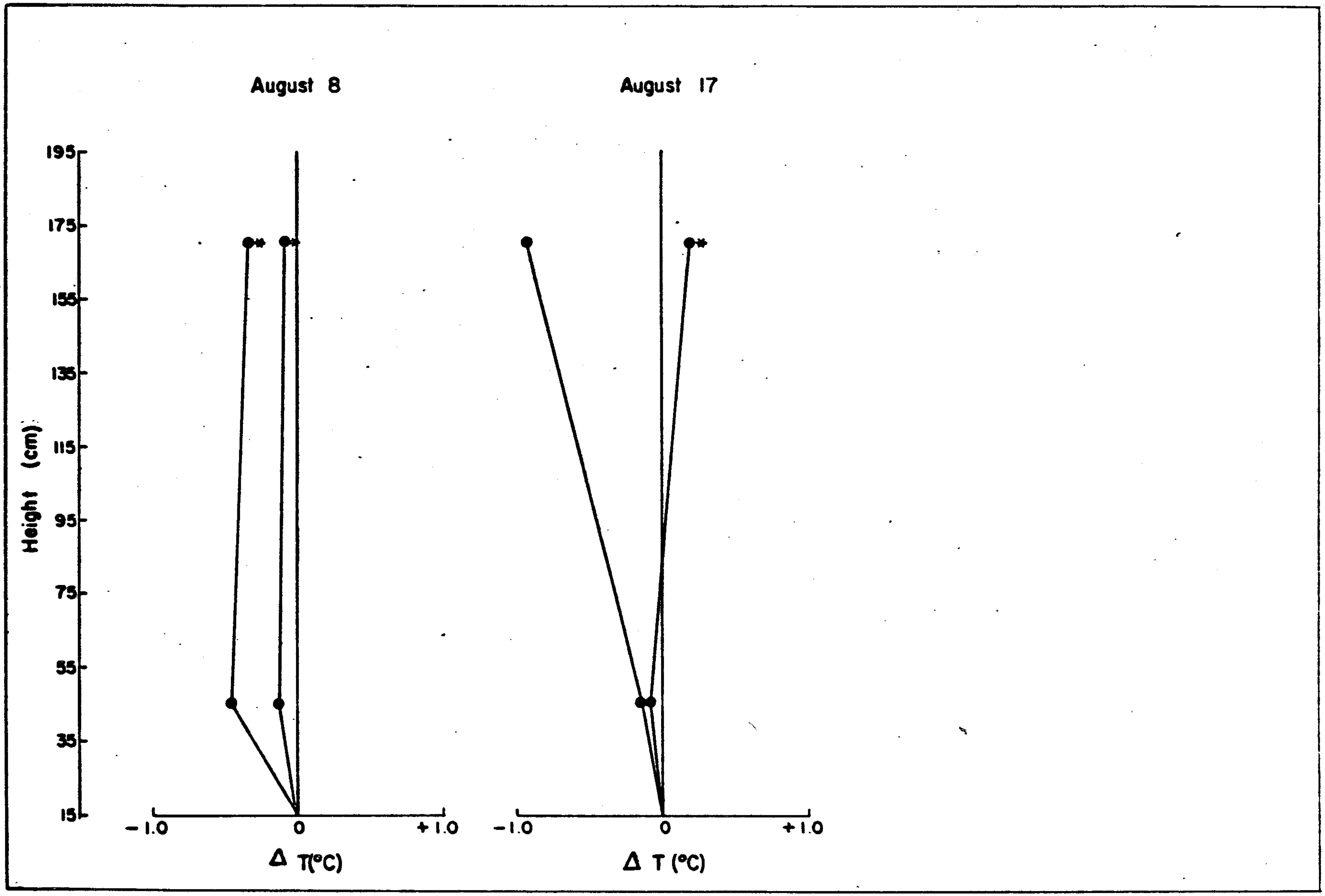
APPENDIX D

Temperature profiles during periods of "apparent advection"


* PROFILE INDICATIVE OF "APPARENT ADVECTION"
July 5
July 13
July 18
Height (cm)
195
175
155
135
115
95
75
55
35
15
-1.0
0
+1.0
Δ T (°C)



July 20
July 27
August 4
Height (cm)
195
175
155
135
115
95
75
55
35
15
−1.0
0
+1.0
Δ T(°C)
*



August 8
August 17
Height (cm)
195
175
155
135
115
95
75
55
35
15
-1.0
0
+1.0
Δ T(°C)
Δ T (°C)

REFERENCES

1. Angus, D.E., 1963: The Influence of meteorological and soil factors on the rate of evapotranspiration of a crop. Ph.D. Thesis, University of California.

2. Bowen, I.S., 1926: The ratio of heat-losses by conduction and by evaporation from any water surface. Phys. Rev., 27, 779-787.

3. Businger, J.A., 1956: Some remarks on Penman's equations for the evapotranspiration. Neth. J. Agr. Sci., 4, 77-80.

4. Chang, Jen-Hu, 1961: Microclimate of sugar cane. Hawaiian Planters' Record, 56, 195-225.

5. Chang, Jen-Hu, 1965: On the study of evapotranspiration and water balance. Erdkunde, 19, 141-150.

6. Deacon, E.L., 1950: The measurement and recording of the heat flux into the soil. Quart. J. Roy. Met. Soc., 76, 479-483.

7. Dyer, A.J., 1967: The turbulent transport of heat and water vapour in an unstable atmosphere. Quart. J. Roy. Met. Soc., 93, 501-508.

8. Dyer, A.J., B.B. Hicks and K.M. King, 1967: The Fluxatron - a revised approach to the measurement of eddy fluxes in the lower atmosphere. J. Appl. Met., 6, 408-413.

9. Elliott, W.P., 1958: The growth of the atmospheric internal boundary layer. Trans. Amer. Geophys. Union, 39, 1048-1054.

10. Fritschen, L.J., and C.H.M. van Bavel, 1963: Evaporation from shallow water and related micrometeorological parameters. J. Appl. Met., 2, 3, 407-411.

11. Fuchs, M., and C.B. Tanner, 1965: Radiation shields for air temperature thermometers. J. Appl. Met., 4, 544-547.

12. Funk, J.P., 1959: Improved polyethylene - shielded net radiometer. J. Sci. Instr., 36, 267-270.

13. Gerber, J.F., and W.L. Decker, 1960: A comparison of evapotranspiration as estimated by the heat budget and measured by the water balance from a corn field. Univ. of Missouri, Final Report USWB, Contract CWB-956.

14. Graham, W.G., and K. M. King, 1961: Fraction of net radiation utilized in evapotranspiration from a corn crop. Soil Sci. Soc. Amer. Proc., 25, 158-160.

15. Handbook of Meteorological Instruments. Part 1. Instruments for Surface Observations. (M.O. 577), 1956, (London).

16. Hare, F.K., 1963: Some estimates of the surface drag over South Jersey farmland. (unpublished manuscript).

17. Harris, D.G., and C. H. M. van Bavel, 1958: A comparison of measured and computed evapotranspiration from bermuda-grass and sweet corn. Agron. Abst., p. 37.

18. House, G.J., N.E. Rider and C.P. Tugwell, 1960: A surface energy - balance computer. Quart. J. Roy. Met. Soc., 86, 215-231.

19. Leopold, A.C., 1961: Senescence in plant development. Science, 134, 1727-1732.

20. Lettau, H.H., 1959: A review of research problems in micrometeorology. Dept. of Meteorology, Univ. of Wisconsin, Final Rpt., Contract DA - 36 - 039 - SC - 80063.

21. McIlroy, I.C., and D. E. Angus, 1964: Grass, water and soil evaporation at Aspendale. Agric. Met., 1, 3, 201-224.

22. Monteith, J.L., 1966: The photosynthesis and transpiration of crops. Expl. Agric., 2, 1-14.

23. Penman, H.L., 1948: Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. (London), 193, A, 120-145.

24. Penman, H.L., 1956: Evaporation: an introductory survey. Neth. Jour. Agr. Sci., 4, 8-29.

25. Penman, H.L., 1962: Weather and crops. Quart. J. Roy. Met. Soc., 88, 377, 209-219.

26. Penman, H.L., D. E. Angus and C.H.M. van Bavel, 1967: Microclimatic factors affecting evaporation and transpiration. Amer. Soc. Agron., Monograph No. 11, 483-505.

27. Pruitt, W.O., and D.E. Angus, 1961: Comparisons of evapotranspiration with solar and net radiation and evaporation from water surfaces. Dept. of Agric. Eng., Univ. of California. First Ann. Rpt. USAEPG, Contract CA - 36 - 039SC - 80334, 74-107.

28. Scholte-Ubing, D.W., 1959: Studies on solar and net radiation and on evapotranspiration of grass. Meded. Landbouwk-School, Wageningen, 59, 1-93.

29. Slatyer, R.O., and I.C. McIlroy, 1961: Practical Microclimatology. UNESCO, C.S.I.R.O., Australia, 310 pp.

30. Swinbank, W.C., and A.J. Dyer, 1967: An experimental study in micro-meteorology. Quart. J. Roy. Met. Soc., 93, 494-500.

31. Tanner, C.B., and E. R. Lemon, 1962: Radiant energy used in evapotranspiration. Agron. J., 54, 207-211.

32. Tanner, C.B., and W. L. Pelton, 1960: Potential evapotranspiration estimates by the approximate energy balance method of Penman. J. Geophys. Res., 65, 3391-3413.

33. van Bavel, C.H.M., 1966: Evaporation and energy balance of alfalfa. Report No. 381, U.S. Department of Agriculture, Phoenix, Arizona.

34. Webb, E.K., 1965: Aerial microclimate. Agr. Met., Met. Monographs, 6, 28, 27-58.

35. Yocum, C.S., L.H. Allen and E.R. Lemon, 1964: Photosynthesis under field conditions. VI. Solar radiation balance and photosynthetic efficiency. Agron. J., 56, 249-253.